東京大學理學部紀要
第二類 地質学 鉱物学 地理学 地球物理学
第十一冊 第二篇

JOURNAL
OF THE
FACULTY OF SCIENCE
UNIVERSITY OF TOKYO

SECTION II
GEOLOGY, MINERALOGY, GEOGRAPHY, GEOPHYSICS

Vol. XI Part 2

TOKYO
Published by the University
November 30, 1958

The "JOURNAL OF THE FACULTY OF SCIENCE" is the continuation of the "JOURNAL OF THE COLLEGE OF SCIENCE" published by this University in forty-five volumes (1887–1925), and is issued in five sections:

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SOME ORDOVICIAN GASTROPODS FROM THE MUN'GYŎNG OR BUNKEI DISTRICT, SOUTH KOREA*

The Cambro-Ordovician Formations and Faunas of South Korea Part V

By

Teiichi KOBAYASHI

With Plate V

Ordovician fossils are exceedingly rare in the Tan'gyang (Tanyo) and Mun'gyŏng districts in the southern part of the Kangwŏn-do (Kogendo) limestone plateau, but SHIRAKI's collection from the latter district contains some gastropods, besides a few indeterminable bryozoans, brachiopods, pelecypods and cephalopods. They were collected by his assistant from dolomitic limestone of the Todon formation at Loc. Kan (咸下), on a small hill northeast of Tot'am-ni, Kaun-myŏn, Mun'gyŏng-kun, Kyŏngsang-bukto, South Korea.**

Seven species of gastropods are distinguished among them as follows:

1. "*Bellerophon*" *aotii* KOBAYASHI, new species
2. *Scalites katoi* (KOBAYASHI)
3. *Scalites irregulare* KOBAYASHI, new species
4. *Helicotoma amanoi* KOBAYASHI, new species
5. *Palaeomphalus keizanensis* (KOBAYASHI)
6. *Lophospira* cfr. *bantatsuensis* KOBAYASHI
7. *Liospira shohakuensis* KOBAYASHI

Because the second, fifth and last species are all known from the Tsuibon limestone, the fossiliferous dolomitic limestone is undoubtedly the correlative of the Tsuibon limestone. These seven species of gastropods are described in this paper. On this occasion *Oxynodiscus sigmoidalis* and *Bucania katoi* are transferred respectively to *Joleandella* and *Loxobucania*.

Superfamily Bellerophontacea

Family Bucaniidae

Genus *Joleandella* PATTE, 1929

Joleandella sigmoidalis (KOBAYASHI)

1934. *Oxynodiscus sigmoidalis* KOBAYASHI, *Jour. Fac. Sci. Imp. Univ. Tokyo, Sect. 2, Vol. 3, Pt. 8*, p. 361, pl. 5, figs. 8–9.

This species agrees with *Oxydiscus* (*Joleandella*) *mansuyi* PATTE (1929, p. 55, pl. 6, figs. 5a–f) in the discoidal shell, especially compressed in the outer side, narrow umbilicus and sigmoidal ornamentation. From these agreements they are

* Received Oct. 16th, 1957; read at the annual meeting of the Palaeontological Society of Japan at Sendai, Feb. 1st, 1958.

** 慶尙北道聞慶郡加恩面都呑里

considered to belong to the same genus. Whether this has a slit-band or not is indeterminable. Its presence is not warranted in PATTE's species either.

His species was procured from *les schistes de Ban Hom, Tonkin*, Indochina, which is presumed either Gotlandian or Devonian. It differs from the Korean species in the coarser ribs which are tuberculate or broken into tubercles and much more widely spaced.

Incidentally, *Oxydiscus* KOKEN, 1889, is according to KNIGHT (1941, pp. 223 & 361), a synonym of *Tropidodiscus* MEEK and WORTHEN 1866. Radial ribs are remarkably sigmoidal in these species of *Joleandella*, but neither in *T. curvilineatus* (CONRAD) nor in *T. imitator* (KOKEN).

Occurrence:—Chikunsan shale at Makkol.

Genus *Loxobucania* KNIGHT, 1942

Loxobucania katoi (KOBAYASHI)

1930. *Bucania katoi* KOBAYASHI, *Japan, Jour. Geol. Geogr. Vol. 7*, p. 87, pl. 8, figs. 6a–c.

KNIGHT erected *Loxobucania* for *Bucania* having ornamentation revolving linear features running normal to the apertural margin and converging upon the slit and selenizone, generally interrupted by growth lamellae. The type specimen is *Bellerophon lindsleyi* SAFFORD to which *B. katoi* agrees in the ornamentation.

Occurrence:—Unkanu Bed; Taesong-ni, Mandal-myŏn, Kangtong-gun, P'yŏngan-namdo, North Korea. (平安南道江東郡晩達面大成里)

Family Bellerophontidae

Genus *Bellerophon* MONTFORT, 1808

"*Bellerophon*" *aotii* KOBAYASHI, new species

Plate V, Figures 1a–b

Description:—Shell small, somewhat globular; spire expanding rapidly; whorl subtriangular in cross section; lateral wall moderately convex, meets with the other wall to form a salient keel on dorsum; umbilicus closed or very small and deep, if opened; aperture scarcely flared. Radial ribs on lateral wall arcuate with forward convexity and abruptly swinging back near keel to form a slit; intervals depressed and much broader than ribs; spiral riblets on the intervals forming small nodes with ribs.

Comparison:—This belongs to REED's Fissidorsata. In the surface scultpture and prominent dorsal carination this species resembles *Cyrtolites lamellifer* LINDSTRÖM (1884, p. 82, pl. 6, figs. 31–38) which is the type of *Temnodiscus* KOKEN, 1896, (KOKEN and PERNER, 1925) and also *Temnodiscus salopinensis* REED (1921, p. 51, pl. 9, fig. 10), but these species of *Temnodiscus* have evolute shells, while this is very involute. In the close coiling of the spire and the broad whorl section it is more similar to *Bellerophon* and even *Pharkidonotus* GIRTY, 1912, although the last genus has no slit-band. This will turn out a new genus, when a better specimen is procured.

Occurrence:—Kan.

Superfamily Pleurotomaricea
Family Raphistomatidae
Subfamilv Raphistominae
Genus *Raphistoma* HALL, 1847

Raphistoma coreanicum KOBAYASHI fits in *Raphistoma* HALL in the essential features, the type of which is *Maclurea striatus* EMMONS. *R. keizanensis* is on the other hand better placed in *Phalaeomphalus* KOKEN. As noted already, *R. katoi* is a scalitoid, although the spire is much lower in it than in *Scalites angulatus* EMMONS, the type of *Scalites* EMMONS, or even in *Scalitina montana* SPIESTERBACH, the type of *Scalitina* SPIESTERBACH.

Genus *Scalites* EMMONS 1842
Scalites katoi (KOBAYASHI)
Plate V, Figures 4a–b

1934. *Raphistoma katoi* KOBAYASHI, *Jour. Fac. Sci. Imp. Univ. Tokyo, Sect. 2, Vol. 3, Pt. 8*, p. 373, pl. 8, figs. 4–16.

This is a common species among the Todonri gastropods, but none shows growth lines. The closest ally to this species is *R. himalaicum* REED which is another scalitoid.

Occurrence:—Kan; Tsuibon beds at Makkol, Saishori and Dotenri.

Scalites irregulare KOBAYASHI, new species
Plate V, Figures 6a–b

This differs from the preceding principally in the abrupt descendance of the last half volution. Accordingly the periphery of this volution forms an angle of about 24 degrees with that of the preceding volution in the lateral view. It is also noteworthy that there is a shallow concavity below the peripheral angulation, where the growth lines are inclined forward, but they become subvertical on the outer wall below the constriction. The upper wall is flat and the peripheral band occupies a quarter of the upper wall where the apeatural margin forms a slit.

The specimen is 3.3 cm. in height and breadth; the upper or outer wall is respectively 8.5 mm. or 19 mm. wide at the aperture. A specimen of *S. katoi* from the same locality is about the same size, but the coiling is regular through the whorl spire.

Occurrence:—Kan.

Subfamily Helicotominae
Genus *Helicotoma* SALTER, 1895
Helicotoma amanoi KOBAYASHI, new species
Plate V, Figures 5a–b, 6a–b

Spire low, composed of 5 or more volutions; early whorls flat-topped, but in the last whorl the upper wall becomes concave and its periphery is well developed into a prominent keel. The lateral wall is subvertical, but gradually inclined inward and forms an obtuse angle with the umbilical wall. The umbilicus is narrower than two-fifths of the diameter. Growth striae on the upper and outer walls are bent back toward the keel to form sinuation.

The holotype in figs. 6a–b is 3.3 cm. across and 2.2 cm. high. The last whorl is 1.8 cm. high or 1.6 cm. high between the basal angulation and the keel or the upper wall of the whorl respectively. The whorl measures 12.5 mm. between the inner suture and outer wall.

This species has the collar along the periphery as commonly seen in *Helicotoma*, but the whorl and the spire also are much taller than usual in *Helicotoma*.

Occurrence:—Kan.

Genus *Palaeomphalus* KOKEN, 1925

Palaeomphalus keizanensis (KOBAYASHI)

Plate V, Figures 8a–b, 9a–b

1934. *Raphistoma keizanensis* KOBAYASHI, *Jour. Fac. Sci. Imp. Univ. Tokyo, Sect. 2, Vol. 3, Pt. 8*, p. 372, pl. 7, figs. 1–7, 14.

A specimen in figs. 8a–b is 4.5 cm. across and composed of more than 5 volutions. The spire, about 2.3 cm. high, is terraced with horizontal upper walls. The lateral and umbilical walls meet to form a blunt angle. The umbilicus thus outlined is a little shorter than the diameter.

The umbilicus is narrower and deeper and the basal carina more pronounced in another specimen in figs. 9a–b. In this specimen the peripheral band is distinctly elevated near the aperture, but it is not collar-shaped. It is clearly seen on the upper and lateral walls that growth lines swing back toward the band.

The low spire, flat horizontal upper walls and the aspects of the peripheral bands suggest *Palaeomphalus* for the proper position of this species. The spire is, however, more rapidly expanding in this species than in *P.gradatus* (KOKEN).

Occurrence:—Kan; Tsuibon beds of Keizanson, Makkol and Saishori.

Family Pleurotomariidae

Subfamily Lophospirinae

Genus *Lophospira* WHITFIELD, 1886

Remarks:—Among 8 species of *Lophospira* which ENDO described from South Manchuria in 1934, *L. elegans*, *L. inconsueta* and *L. tenuis* are all quite distinct from the already known species from Eastern Asia. *L. similator* is, however, so similar to *L.* (*Pagodispira*) *tetracarina* that they appear to me to belong to an identical species. *L. yabei* and *L. minuta* look very much like *L. morrisi* and *L. grabaui* respectively. I fear that *L. compressa* and *L. ozakii* are deformed *L. subpulchellus*. The older species of Eastern Asia have already been discussed in 1934.

Lophospira cfr. *bantatsuensis* KOBAYASHI

Plate V, Figure 3

1930. cfr. *Lophospira bantatsuensis* KOBAYASHI, *Japan. Jour. Geol. Geogr. Vol. 7*, p. 88, pl. 9, figs. 4–5.

Because the shell is compressed laterally and somewhat obliquely, the apical angle measures 68 or 82 degrees in a way or another. An upper whorl is embraced by a lower one as much as seen in the specimen in fig. 4, pl. 9, 1930. The marginal carina is trilineate and protruded; lateral wall very steeply inclined, somewhat concave and separated from the lower wall by an obtuse angulation.

Aperture and umbilicus unknown.

This resembles *L. morrisi* GRABAU, but the lateral wall is more inclined in that species. In the subvertical lateral wall, it is similar to *L. endoi* KOBAYASHI, but the apical angle is larger and the spire growing more rapidly in this species.

Occurrence:—Kan.

Subfamily Eotomariinae

Genus *Liospira* ULRICH and SCOFIELD, 1897

Liospira shohakuensis KOBAYASHI

Plate V, Figures 2a–c

1934. *Liospira shohakuensis* KOBAYASHI, *Jour. Fac. Sci. Imp. Univ. Tokyo, Sect. 2, Vol. 3, Pt. 8*, p. 368, pl. 7, figs. 12–13, 15–16.

A Steinkern agrees with the holotype of this species except the peripheral angulation which is somewhat more rounded in the Saishori specimen.

Occurrence:—Kan; Tsuibon beds at Saishori.

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T. Kobayashi

Some Ordovician Gastropods from the Mun'gyŏng or Bunkei District, South Korea

The Cambro-Ordovician Formations and Faunas of South Korean, Part V

Plate V

Explanation of Plate V

"*Bellerophon*" *aotii* KOBAYASHI, new species .... p. 86
Figures 1a–b. Dorsal and lateral views. ×1.5.

Liospira shohakuensis KOBAYASHI .... p. 89
Figures 2a–c. Lateral, apical and dorsal views. ×2.

Lophospira cfr. *bantatsuensis* KOBAYASHI .... p. 88
Figures 3. Lateral view. ×1.5.

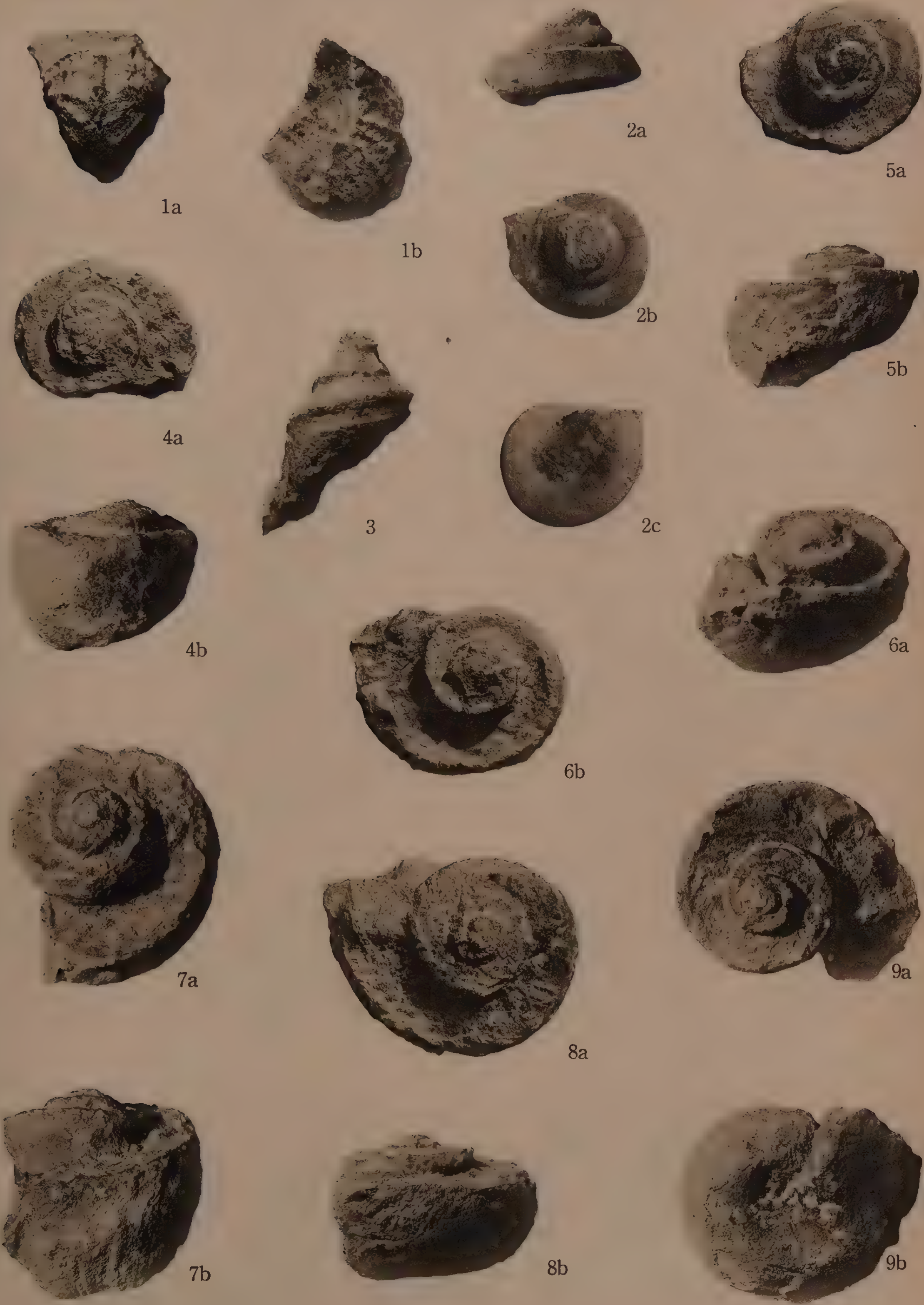
Scalites katoi (KOBAYASHI) .... p. 87
Figures 4a–c. Apical and lateral views. ×1.

Helicotoma amanoi KOBAYASHI, new species .... p. 87
Figures 5a–b. Apical and lateral views. ×1.
Figures 6a–b. Oblique-lateral and apical views. ×1.

Scalites irregulare KOBAYASHI, new species .... p. 87
Figures 7a–b. Apical and lateral views. ×1.

Palaeomphalus keizanensis (KOBAYASHI) .... p. 88
Figures 8a–b. Apical and lateral views. ×1.
Figures 9a–b. Apical and umbilical views. ×1.

All specimens collected from Loc. Kan. (咸下), Northeast of Tot'am-ni, Kaun-myŏn, Mun'gyŏng County, Kyŏngsang-Bukto, South Korea (慶尙北道聞慶郡加恩面都呑里北東方) and stored in the Geological Institute, University of Tokyo.


1a
1b
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6a
6b
7a
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8b
9b

JAPANESE HALYSITIDAE*

By

Takashi HAMADA

With Five Plates

Table of Contents

I. Introduction and Acknowledgements

In Japan, ONUKI was the first to discover the Gotlandian deposits yielding chain corals. It was made in 1937 in the Kitakami mountains, northeastern Honshû (ONUKI, 1937, p. 601). *Halysites* therein were tentatively assigned for *H.* cfr. *parallelus*, and *H.* sp. indet. by SUGIYAMA (1937, p. 519, listed). Subsequently

* Received Jan. 6, 1958; read at the Annual Meeting of the Palaeontological Society of Japan, at Sendai, Feb. 1, 1958.

in 1940, KOBAYASHI and IWAYA discovered a *Halysites*-bearing limestone at Imose in the Sakawa basin, Shikoku Island. This was the first report of the occurrence of the Gotlandian deposits in the outer zone of Southwest Japan. In the same year SUGIYAMA published his work on the Gotlandian fauna of the Kitakami mountains in which three chain corals, viz., *Halysites kitakamiensis*, *H. japonicus* and *H.* sp. indet. were included. SUGIYAMA also examined the coral fauna of the Imose limestone bed and reported a *Halysites* ? sp.

Since then several new localities of the Gotlandian rocks with *Halysites kitakamiensis* have been found in the outer zone of Southwest Japan as indicated in Text-figure 1. Recently, NODA (1952) reported the occurrence of three halysitids from the limestone at the Yokokura-yama, Kôchi Prefecture. They were *Halysites kitakamiensis*, *H. japonicus* and *H. shikokuensis*, among which the last is a new species but no description was accompanied. Subsequently the present writer described *Halysites kitakamiensis* from the Kuraoka district, Miyazaki Prefecture, Central Kyûshû (1956).

In spite of the increase of localities as above mentioned no intensive study has been done on the Gotlandian palaeontology and biostratigraphy since SUGIYAMA's work in 1940, although the similarity of the Gotlandian faunas in the outer zone of Southwest Japan to the Salopian fauna of the Kitakami was noticed by some geologists.

In order to illuminate the Gotlandian faunas in Japan, the writer has commenced the palaeontological study in 1955 from the tabulate corals. In this paper, four new and six known und two uncertain forms of Japanese chain corals in four genera belonging to three sufamilies are described. *Falsicatenipora* is a new genus of the Schedohalysitinae HAMADA, 1957, characterized by the presence of mesocorallites (=" gonopores " by ETHERIDGE) and the absence of microcorallites. On this occasion, a Chinese and a Korean halysitid are described.

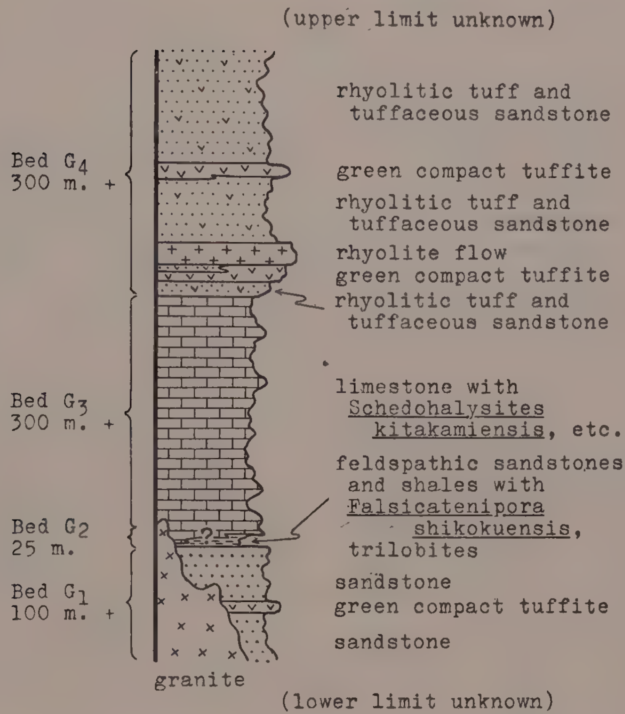
The Asiatic and Australian chain corals are listed with tentative generic assignment. The writer emphasized the close affinity among these faunas in the western Pacific provinces. Their characteristics are in the predominance of the slender chain corals as typified by *Schedohalysites kitakamiensis*. He proposes a name " Asia-Australian Sea " for the Gotlandian sea of the provinces.

The writer sincerely thanks to Professor Teiichi KOBAYASHI of the Geological Institute, University of Tôkyô for his constant guidance in the course of the study. He is also indebted to Professor Shôshirô HANZAWA of the Geological and Paleontological Institute of the Tôhoku University who kindly permitted the writer to examine the specimens kept in his institute, to Dr. Hisakatsu YABE for his stimulation which greatly accelerated this work, and to Messrs M. SAITÔ and N. KAMBE of the Geological Survey of Japan for their generous assistance in his field works.

II. Gotlandian Stratigraphy of the Outer Zone of Southwest Japan

The fossiliferous Gotlandian rocks occur in the outer zone of Southwest Japan as a chain of small masses signifying the so-called Kurosegawa Structural Zone (ISHII et al., 1952; ICHIKAWA et al., 1956). Their exposures are, however, so fragmentary to figure out a complete succession of the Gotlandian strata. The limestones and some shales are fossiliferous, but the faunal analyses are far from complete.

The writer has been engaged in the field works at the Kuraoka district,



Text-figure 2. A generalized columnar section of the Gion-yama formation.

Text-figure 1. Locality map of the Gotlandian rocks in Japan. Each locality numbers are collated with the numbers in the articles. K: Kawauti series in the Kitakami mountains.

Miyazaki Prefecture in these three years. There the Gotlandian Gion-yama formation (SAITÔ and KAMBE, 1952) is not much disturbed and he succeeded to divide it into the following four beds by lithology and faunas. A generalized columnar section of the formation is shown in Text-figure 2.

Bed G_4 (300 m.+):—Thick rhyolitic tuffs and tuffaceous sandstones with some intercalations of green compact tuffites having vitroclastic texture. A rhyolite flow about 30 m. thick is in the lower part. Cut by a fault, the upper limit is unknown. No fossil was obtained except for a few radiolarian remains.

The green compact tuffites resembling green adinole or chert serve for a key to the Gotlandian in the outer zone of Southwest Japan.

Bed G_3 (300 m.+):—Thick massive limestone containing *Falsicatenipora japonica*, *Schedohalysites kitakamiensis*, *Halysites tenuis*, *H. bellulus*, *Clathrodictyon*, *Favosites*, *Heliolites*, *Tryplasma*, *Zelophyllum*, *Conchidium*, and so on. Above all, remarkable is the abundance of *Schedohalysites kitakamiensis*.

The limestone is pale grey in general but often pinkish or greenish probably stained with tuffaceous materials. White saccharoidal limestone was found near the contact with granitic rock member of the Yokokura igneous group (KOBAYASHI, 1941). They are quite different from the limestones in the Kitakami mountains in colour. Due to carbonaceous matter or other impurity the latter is always black or dark grey. The great difference must be attributed to the difference of the depositional site.

Bed G_2 (25 m.):—Thin alternation of feldspathic sandstones and shales with many lenses or nodules of small impure limestone which contain many fossils

Table 1. Tentative correlation of the Gotlandian deposits in the outer zone of Southwest Japan.

Beds \ Locs.	1	2	3	4*a*	4*b*	5	6	7	8*a*	8*b*	9	10	11	12*a*	12*b*	13
G_4			×	×						×			×			
G_3	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
G_2				×	×							×	×			×
G_1													×			

1: Nabae-bana, Hirokawa-machi, Arita-gun, Wakayama Prefecture.
2: Tachikawa, Yokose-machi, Katsura-gun, Tokushima Pref.
3: Imose, Hidaka-mura, Takaoka-gun, Kôchi Pref.
4*a*: Main part of Yokokura-yama, Ochi-machi, Takaoka-gun, Kôchi Pref.
4*b*: Northwestern side of Yokokura-yama, Ochi-machi.
5*: Northwest of Ôdaira, Ôgiri, Ochi-machi.
6: Ôtô, Ôgiri, Ochi-machi.
7*: Matsu-tani, Yuzuhara-mura, Takaoka-gun, Kôchi Pref.
8*a*: East of Mitaki-yama, Kubono, Kurosegawamura, Higashiuwa-gun, Ehime Pref.
8*b*: Southwest of Mitaki-yama, Kurosegawa-mura.
9: Yoshinosawa, Doi, Kurosegawa-mura, Higashiuwa-gun, Ehime Pref.
10: Okanaru, Nomura-machi, Higashiuwa-gun, Ehime Pref.
11: Gion-yama, Kuraoka, Gokase-machi, Nishiusuki-gun, Miyazaki Pref.
12*a*: West of Take, Fukami, Shimomatsukuma-mura, Yatsushiro-gun, Kumamoto Pref.
12*b*: Northeast of Kami-fukami, Fukami, Shimomatsukuma-mura.
13: Northeast of Kawaguchi, Shimomatsukuma-mura.

* Newly found by HIRATA, M., 1958: Some Important New Facts from the Chichibu Zone of the Central Part of Shikoku (in Japanese). *Chikyū-kagaku, No. 36*, pp. 22–24.

Table 2. Stratigraphy of the Gotlandians in Japan.

Northeast Japan										Outer Zone of Southwest Japan		
Kitakami Mountains										Yokokura-yama	Kuraoka	
ONUKI, Y. (1938)			SUGIYAMA, T. (1940)				ÔKUBO, M. (1949)			NODA, M. (1955)	HAMADA, T. (1958)	
Kawautian (1400 m.+)	V	Downtonian		Nakazato Series		Devonian	Takainari System	III Group (534.1 m.)	Middle Devonian	(unknown)	(unknown)	Devonian
	IV			Ôno Series								
	III			Takainari Series		Downtonian		II Group (354.6 m.)			G_4 (300 m. ca.)	Upper-Middle Ludlovian ?
	II	Salopian	Kawauti Series	5. *Solenopora*-ls.		Salopian		I Group (40.0 m.+)	Gotlandian	Kusugami Ser.*	G_3 (300 m. ca.)	Lower Ludlovian
				4. *Encrinurus*-bed								
				3. *Halysites*-ls.	(3)							
					(2)							
					(1)							
	I			2. *Clathrodictyon*-ls.							G_2 (25 m.)	Wenlockian ?
				1. *Favosites*-ls.						Morikawa Ser.**	G_1 (100 m.+)	

* According to my field survey, NODA's Kusugami and Morikawa series include some metamorphic rocks probably of the Permo-Carboniferous age. These metamorphic rocks are in fault contact with the Gotlandian formation.

** NODA's Mori Series in 1952.

such as halysitids, favositids, heliolitids, gastropods, pelecypods, brachiopods, hydrozoa, and encrinurid trilobite. The Halysitidae are represented by the followings:

Falsicatenipora shikokuensis NODA and HAMADA, sp. nov.
Acanthohalysites kuraokensis HAMADA, sp. nov.
Halysites sp. indet.
Catenipora ? sp. indet.

Bed G_1 (100 m.+):—Heavily massive, medium to coarse grained sandstones, less tuffaceous than those of the bed G_4. A thin layer of green compact tuffite is intercalated. Intruded by granitic rock, a member of the Yokokura igneous group, the base is unknown.

Some thirteen localities of the fossiliferous Gotlandian rocks have so far been known from the outer zone of Southwest Japan. The writer visited most of them and collected fossils. Taking the Kuraoka sequence for the standard correlation is attempted as shown in Table I.

Due to the lack of graptolites or any other keen indices the chronolgy of these formations cannot be in great accuracy. SUGIYAMA (1940) determined the age of the Kawauti series in the Kitakami mountains at the Middle Gotlandian by comparison of the faunal assemblage of 23 genera to those in Asia, western Europe, North America and Australia. However, no Salopian index was included.

The Gotlandian stratigraphy in Japan done by several authors is schematized as shown in Table II.

There are two reasons as to why the writer puts G_3 into Lower Ludlovian. 1) Slender cylindrical tryplasmatids, *Zelophyllum* spp., are newly obtained from limestones G_3 at the Kuraoka district as well as Yokokura-yama where they are usually accompanied by *Schedohalysites kitakamiensis*. This genus is characteristic in the *Zelophyllum-Kodonophyllum*-Stufe at Gotland. They were found also on the western and eastern slopes of the Urals, and SOSHKINA (1937) correlated this fossil bed to the Lower Ludlovian in the Gotland section. *Z. lindströmi* WANG is reported from the Gotlandian of Yunnan. 2) A large pentamerid, *Conchidium* cf. *knightii* (SOWERBY), was found from the upper part of the bed G_3. This species is a characteristic member in the Upper Gotlandian of Wales and Western England (especially in the Aymestry limestone), of New South Wales, Australia and also of the Salair mountains and the Russian Altai. Besides, closely related forms are known from the same horizon in Southeast Alaska, Novaya Zemlya, and so on. Thus the occurrence of this brachiopod shows that the bed G_3 at the Kuraoka district is probably not older than Lower Ludlovian.

The *Halysites*-limestones in the Kitakami mountains can be definitely correlated to the bed G_3, both characterized by *Schedohalyites kitakamiensis*, although there is slight difference in lithology as above noted.

Several fossil beds known in the Kitakami mountains are apparently unrepresented in the limestones of the Kuraoka district in spite of the great thickness of the latter. *Encrinurus* sp. from the bed G_2 disagrees with SUGIYAMA's *Encrinurus* (*Coronocephalus*) *kitakamiensis* from the bed G_4 in the Kawauti series not only in size but also in some other aspects. This may imply chronological difference.

III. Note on the Terms for Corallites of the Halysitidae

In 1904 ETHERIDGE (1904b, pp. 18, 19) established the term "gonopore" for the mesocorallite at the angle of the fenestrule with an excellent definition as quoted below:—

"I employ this term to distinguish the corallites, more often than not, occupying the angles of the fenestrules, and from which in nearly every case new chains arise; they always lie between two autopores. I find that, within certain limits, they are of a different shape to either the autopores or mesopores of a given species, and are always either intermediate in size, or nearly equal to that of the autopores. Furtheremore, in some cases, although not in all, the tabulae are differently spaced to those of the other tubes. If, therefore, a distinction is to be made between the "normal" corallites and the "interstitial tubes", or "tubules", I fail to see why a third group of zooids should not be recognised, provided such zooids can be shown to prossess distinctive features of their own. They are always larger than the mesopores, and usually less than the autopores, are always non-septate, and present in all the Australian species; but in three of the latter, these gonopores are not invariably present at every fenestrule angle. They may be recognised by their outline, triangular or quadrangular, irrespective of position; but the commoner outline is polygonal, the hexagonal predominating. ..."

Ignoring this statement, many authors used the customary term "mesocorallite" or "mesopore" including the gonopore. The writer thinks that the term "gonopore", however, is not suitable to apply to the third group of zooids by ETHERIDGE, because it is indetermined whether the function of that organ is sexual reproduction or not. "Gono-" means sex. ETHERIDGE noted that a new chain appears always from a "gonopore". It is true, but there are many chain corals without "gonopore" and their new chains were brought forth from normal corallites or the "autopores", as seen in *Catenipora escharoides*, *C. rubra*, and so on.

The writer considers that the presence of the third zooid in some Halysitidae bears great importance as later mentioned. By this reason he thinks wise to distinguish the term "mesocorallite" *sensu stricto* from "mesocorallite" *sensu lato*. The latter includes ETHERIDGE's "mesopore" and "gonopore", while the former means one kind of interstitial tubuli other than microcorallite ("mesopore" by ETHERIDGE), i.e. "gonopore".

Recently, HILL and STUMM (1956) accepted the term "microcorallite" in the sense of ETHERIDGE's mesopore. "Microcorallite" was used by AMSDEN (1949), but his usage was not clear whether it represents the "mesopore" or "gonopore" by ETHERIDGE. His "macrocorallite" stands for the autocorallite or autopore in general usage.

To avoid confusion in description of corallites of the Halysitidae the terms are here accepted as follows:—

macrcorallite: autocorallite, autopore, corallite.
mesocorallite: gonopore.
microcorallite: pars. of general usage of mesopore, mesocorallite, interstitial tube, interstitial tubule, tubule.

The term "corallites" should be used in *sensu lato* including three kinds of zooids, unless the usage of the term is restricted to the monomorphic Cateniporinae.

IV. Systematic Description

Family Halysitidae M. EDWARDS and HAIME, 1850

Subfamily Cateniporinae HAMADA, 1957

Genus *Catenipora* LAMARCK, 1816

Catenipora ? sp. indet.

Plate VI, Figure 6.

Description:—A single specimen at hand. Corallum subglobose; medium in size, about 4 cm. in diameter and 3 cm. in height. Fenestrules rather large,

5×7 mm., 3×8 mm., etc., and polygonal or irregular in shape. Corallite rectangular in cross section, 0.75×1.0 mm. in mean size. Septal spinules present? Outer wall of corallite apparently smooth, but with faint transverse striation. Junction of corallites not so constricted that the surface of the chains is seldom undulated in cross section. Microcorallites and mesocorallites not observed. Tabulae in corallite straight, horizontal and 0.7–1.0 mm. apart from one another in longitudinal section.

Remarks:—The specimen is recrystallized. The corallum is largely exposed on rock surface as seen in Figure 6 on Plate VI. The brittleness of the specimen prevents preparing any thin section. In external appearances it is somewhat similar to *Schedohalysites kiatakamiensis*, but appears to have no microcorallite and mesocorallite.

Occurrence:—From a calcareous lens in sandy shale of the G_2 at the western foot of the Gion-yama (loc. 11).

Repository:—PCa 7250.

Subfamily Schedohalysitinae HAMADA, 1957

Genus *Falsicatenipora*, nov.

Type Species:—*Halysites japonicus* SUGIYAMA, 1940, *Sci. Rep. Tôhoku Imp. Univ., Second Ser. (Geol.), Vol. 21, No. 2*, p. 131, pl. XXVIII (XVI), figs. 1, 2; pl. XXX (XVIII), figs. 6–8.

Diagnosis:—Schedohalysitinae with mesocorallites but without microcorallites.

Remarks:—Insofar as the writer is aware, seven forms may belong to the present genus as follows:—

1) *Halysites chillagonsis* ETHERIDGE, 1904, pl. V, figs. 3, 4; pl. VIII, figs. 3, 4: pl. IX, fig. 3. Chillagoe, Queensland, Australia. Gotlandian.
2) *Halysites aequabilis* TEICHERT, 1937, pl. VIII, fig. 2; pl. IX, fig. 4. Iglulik Island, Arctic Canada. Up. Ordovician?
3) *Halysites japonicus* SUGIYAMA, 1940. Kitakami mountains, Northeast Japan. Mid. Gotlandian.
4) *Halysites* sp. MILLER and YOUNGQUIST, 1947, pl. 7, fig. 9. Sutton Islands, Dolphin and Union Strait, Arctic Canada. Ordovician.
5) *Halysites* sp. indet. HILL, 1954, pl. IV, fig. 7. Yarrangobilly, New South Wales, Australia. Wenlockian or possibly Ludlovian.
6) *Catenipora hillae* HAMADA, 1957 (*Halysites* sp. cf. *australis* by HILL), HILL, 1954, pl. IV, figs. 8a, b. Long Plain, New South Wales, Australia. Wenlockian or Ludlovian.
7) *Falsicatenipora shikokuensis* NODA and HAMADA, sp. nov. Yokokura-yama, Shikoku, and Gion-yama, Kyûshû in outer zone of Southwest Japan. Bed G_2 (Wenlockian?).

Among them, forms 1, 2 and 3 were previously placed in *Catenipora* by the writer (1957b, c).

It is a remarkable fact that most forms of the genus are known from Middle or Upper Gotlandian rocks of Australia and Japan. There are only two Upper Ordovician forms from Arctic Canada. Concerning *Halysites aequabilis* there is a slight question as to whether the mesocorallite-like cross section in TEICHERT's fig. 4 on plate 9 is a young corallite section of interstitial increase.

Phylogenetically the genus links monomorphic genus *Catenipora* with *Schedohalysites* which is provided with mesocorallite and microcorallite in a part and without them in another part of a corallum. In Japan and Australia *Falsicatenipora* seems to represent the most primitive form of the Halysitidae. The genus had

appeared in Arctic Canada already in the Upper Ordovician, whence the Gotlandian Halysitinae were probably derived, not through the *Schedohalysites*-stage.

Falsicatenipora japonica (SUGIYAMA), 1940

Plate VI, Figures 1, 2.

*Halysites japonicus** SUGIYAMA, 1940. Reg. No. 39524, Tôhoku University, Sendai. (See reference for type species of the genus.)

SUGIYAMA's original description is as follows:—

Form and surface characters of corallum unknown. Anastomosed corallites in a single chain more or less flexuous, catenated structure not distinct. Meshes (fenestrules in this paper) probably forming pentagon or heptagon ?, and each chain with 2–5 corallites. Corallites anastomosed without tubules (microcorallites), mostly subrectangular or somewhat oval-like in outline, 1–1.3×1.5–2.3 mm. in size. Septa quite absent. Walls 0.25 mm. on an average and as thick as intercorallites wall. Walls of gonopores (mesocorallites) with triangular outline, and more or less slender than those of corallites. Tabulae rather distant, horizontal, and about 5 of them in 2 mm. on an average.

Type Locality:—Higuti-zawa in Kawauti, Hikoroiti-mura, Kesen-gun, Iwate Prefecture, Northeastern Honshû (loc. K in Text-figure 2 on page 93). *Halysites*-limestone (3).

Remarks:—SUGIYAMA allocated this species in *Halysites*, s.l. The writer (1957) has once referred it to *Catenipora* with query. Now this can be placed at *Falsicatenipora* with confidence. The materials collected from the outer zone of Southwest Japan are also diagnostic. Incidentally, SUGIYAMA's measurement of 2.3 mm. in corallite length seems to be made on an oblique section.

Distribution:—Kitakami mountains (loc. K), Northeast Japan and locs. 3, 4a, 6 and 11 in Southwest Japan. Bed G_3 (Lower Ludlovian).

Repository:—PCa 7251, 7252.

Falsicatenipora shikokuensis NODA and HAMADA, sp. nov.

Plate VI, Figures 4, 5; Plate VII, Figures 1–7.

Halysites shikokuensis NODA, 1952, *Jour. Geol. Soc. Japan, Vol. 58, No. 682*, p. 322 (listed).

Description:—Corallum small, massive or hemispherical, and sometimes cylindrical and *Thamnopora*-like (Plate VII, Figures 4, 5). Longitudinal section of the corallum often fan-shaped suggesting rapid virgation of corallites (Plate VII, Figure 6). Corallum 7×5×2 cm. at the maximum and commonly about 2×2×2 cm. Fenestrules small, regularly tetragonal to hexagonal and 1 mm. in diameter at the smallest. A chain of corallites composed mostly of 1 or 2 macrocorallites and rarely of 3 or more. Macrocorallites very small and slender, 0.3—0.5×0.6—1.0 mm. in size, rectangular in cross section. Microcorallites exceedingly rare and mesocorallites observable by their triangular sections at fenestrule angles. The junctions of the corallites are scarcely constricted and the chain looks nearly straight. Visceral chambers of macrocorallites somewhat elliptical in cross section, due to slight thickening of macrocorallite walls at their junctions (Plate VI, Figure 4). Wall medium in thickness, 0.1—0.15 mm. Wall surfaces of corallite tubes with weak longitudinal striae (Plate VII, Figure 5). Tabulae in macrocoral-

* *Halysites japonica* in SUGIYAMA's explanation of plate XXX (XVIII) seems to be a misprint for *H. japonicus*.

lites horizontal, complete; 5–8 of them countable in every one millimeter in longitudinal section. Tabulae a little closer in mesocorallites than in macrocorallites. Septal spinules seen in a few macrocorallites. Calyces of corallites nearly as deep as twice the minor diameters of corallites (Plate VI, Figure 5).

Remarks:—From *F. japonica* this form is readily distinguished by the small size of fenestrule and corallite. On this account this resembles *Catenipora minima* (TCHERNYCHEV) from the Gotlandian of Novaya Zemlya, Severnaya Zemlya, which possesses horizontal, slightly concave or convex tabulae. In the present form they are always horizontal. The Russian species agrees with this in other characters, but nothing is mentioned of the mesocorallite. Unfortunately the writer cannot see its original figure. Therefore it is left undetermined whether *minima* belongs to *Falsicatenipora* or not.

HILL (1954) reported four chain corals. Three of them are *Halysites* cf. *lithostrotionoides* (now *Schedohalysites yarrangobillyensis* HAMADA, 1957) and *Halysites* 2 spp. indet. resembling the present form with regard to their corallite size and small fenestrules. But the first differs from this in the presence of microcorallites, and the two others in the corallite shape and septal spinules, though one of them belongs to *Falsicatenipora* as above listed. *Halysites* cf. *australis* is, however, more similar to this species than *Halysites australis*. Her description agrees well with the writer's observations on this species except for a little difference in corallite size and more rectangular macrocorallite section. Mesocorallites are clearly recognized in it. Therefore this Australian species, which has been once tentatively assigned for *Catenipora hillae* by the writer (1957), must be transfered to the present genus from *Catenipora*.

Distribution:—Middle? Gotlandian G_2 sandy limestones at the Yokokura-yama (loc. 4b) and the limestone lenses in G_2 sandy shales of the western foot of the Gion-yama (loc. 11), outer zone of Southwest Japan.

Repository:—Holotype, PCa 7253; paratypes, PCa 7254–9, 7263.

Genus *Schedohalysites* HAMADA, 1957

Schedohalysites kitakamiensis (SUGIYAMA), 1940

Plate VI, Figure 3; Plate VIII, Figures 4, 5.

Halysites kitakamiensis SUGIYAMA, 1940, *Sci. Rep. Tôhoku Imp. Univ., Second Ser. (Geol.), Vol. 21, No. 2*, pp. 129–131, pl. XXVII (XV), figs. 4–9; pl. XXVIII (XVI), figs. 3–8; pl. XXX (XVIII), fig. 14, text-fig. 6.

Halysites kitakamiensis, HAMADA, 1956, *Japan. Jour. Geol. Geogr., Vol. 27, Nos. 2–4*, pp. 134–140, pl. 9, figs. 1–6, text-fig. 1.

The reader is referred to the last reference (HAMADA, 1956) for the diagnosis of this species. The terms autocorallite and mesocorallite in that are macrocorallite and mesocorallite in this paper.

Remarks:—Many specimens of this species were collected at various localities in the outer zone of Southwest Japan. As the results of the examination of the fresh materials, it becomes clear that the thin wall in the original description is not original feature, and in some well preserved specimens the wall is medium in thickness as seen in Figures 4 and 5 on Plate VIII. Visceral chambers of macrocorallites take elliptical shape by thickening of the wall at the junctions of corallites. A longitudinal section of corallum (Plate VI, Figure 3) shows the virgation of corallites.

Distribution:—*Halysites*-limestones at loc. K in the Kitakami mountains, Northeast Japan, and G_3 of the outer zone of Southwest Japan.

Repository:—PCa 7260~2, 7264~8.

Subfamily Halysitinae M. EDWARDS and HAIME, 1850,
emend. HAMADA, 1957

Genus *Acanthohalysites* HAMADA, 1957

Acanthohalysites kuraokensis, sp. nov.

Plate VIII, Figures 1–3.

Description:—A single imperfect specimen is at hand. Corallum massive, compact, medium in size; 4×4×5 cm. Fenestrules small, irregularly polygonal, 1.0×1.6 mm., 1.4×1.6 mm., 1.4×2.0 mm., and so on. A chain on one side of a fenestrule composed of one or two macrocorallites. Macrocorallites beautifully oval in cross section, 0.7×0.8–0.9 mm. in size. Sides of corallite chain appear strongly undulate because small microcorallites are intervened between macrocorallites. Microcorallites quadrate or parallelogramatic, about 0.1×0.1–0.2 mm. in size. Mesocorallites well developed, triangular or depressed hexagonal in transverse section. Corallite wall heavy, 0.1–0.15 mm. in thickness, where 0.04 mm. thick is occupied by epitheca. Surface of the wall unobservable. In some macrocorallites septal spinules represented byshort projections in cross section. Tabulae rather thin, complete, horizontal, 0.3–0.4 mm. apart from one another in macrocorallites and about 0.2 mm. apart in microcorallites.

Remarks:—This species is distinct from others in the small fenestrules and beautifully oval macrocorallite section. HILL's description of *Halysites* sp. indet. from the vicinity of Cooinbil Homestead, Long Plain, New South Wales (1954, p. p. 39, pl. IV, fig. 9) coincides with this. The writer dares to say that they are conspecific. Another Australian massive compact species is *Halysites brevicatenatus* HILL which is similar to this in appearance, but its fenestrules are smaller than macrocorallites in cross section. It is probable to belong it to *Densoporites* as mentioned elsewhere (HAMADA, 1957b, c). North American *Acanthohalysites encrustans* (BUEHLER) differs from this in the larger macrocorallite and strong upward convexity of tabulae in the microcorallites, through it also looks like this in the oval macrocorallite section and small fenestrules.

Occurrence:—Limestone lenses in sandy shale at a road cut, on the western foot of the Gion-yama (loc. 11). Middle ? Gotlandian G_2, with *Encrinurus* sp.

Repository:—Holotype PCa 7269.

Genus *Halysites* FISCHER VON WALDHEIM, 1813

Halysites cratus ETHERIDGE, 1904

Plate X, Figures 5, 6a, b.

Halysites cratus ETHERIDGE jun., 1904, *Mem. Geol. Surv. New South Wales, Palaeont., No. 13, Pt. 1*, pp. 27–29, pl. I, fig. 1; pl. IV, figs. 3, 4; pl. VI, figs. 5, 6.

Halysites cf. *cratus*, GRABAU, 1925, *Bull. Geol. Surv. China, No. 7*, p. 77.

Halysites cratus, BUEHLER, 1955, *Peabody Mus. Nat. Hist. Bull., No. 8*, pp. 53–54.

Description:—Corallum massive, 8×4×4 cm. in size (imperfect specimen). Fenestrules irregularly polygonal, medium in size, 5×10 mm., 7×12 mm., and so on. A chain on one side of a fenestrule slightly curved in transverse section and composed of 2 to 4 macrocorallites, 5 in rare instances. Macrocorallites rounded oval in cross section, about 1.6 mm. long by 1.4 mm. wide. Chains of

corallites constricted at the junction of two macrocorallites where occupies a microcorallite of about 0.3×0.8 mm. in mean size. Mesocorallites large and blunt triangular in transverse outline. Corallite walls thin, and about 0.1 mm.; their surface faintly striated longitudinally. No septal spinules detected. Tabulae moderately thick, complete, horizontal; their intervals 0.4 to 0.6 mm. in macrocorallites, and 0.3 to 0.4 mm. in microcorallites.

Remarks:—The Japanese form coincides with ETHERIDGE's original description in every character except for a slight difference in the wall surface. The type species was obtained from Ph. Copper Hill, and Ph. Gamboola, Co. Wellington, Australia.

GRABAU (1925) described *Halysites* cf. *cratus* from the Middle Gotlandian Sintan Shale which resembles this so closely that they are presumed conspecific.

The neotype of *Halysites catenularius* (LINNAEUS) recently described by THOMAS and SMITH (1954, pp. 766, 767, pl. XX, figs. 1a–c) is somewhat similar to this species. It has also rounded oval macrocorallite section, but differs from this in its labyrinthine lacunae and rather thick corallite walls.

Occurrence:—Limestone at Fukami (loc. 12b). Probably the lower Upper Gotlandian G_3.

Repository:—PCa 7271.

Halysites süssmilchi ETHERIDGE, 1904

Plate IX, Figures 1–4.

Halysites Süssmilchi ETHERIDGE jun., 1904, *Mem. Geol. Surv. New South Wales, Palaeont., No. 13. Pt. 1*, pp. 26, 27, pl. III, figs. 3, 4; pl. VII, figs. 1–3.

Halysites sussmilchi, BUEHLER, 1955, *Peabody Mus. Nat. Hist., Bull. No. 8*, pp.52–53.

Description:—Corallum massive, forming tall tabular colonies up to a size about 10×15×15 cm. and showing almost parallel or slightly radiate growth of the corallites. Fenestrules irregular, somewhat labyrinthine, and composed of long winding chains each of which consists of 5–9 macrocorallites (Plate IX, Figure 1). Macrocorallites small, eye-shaped and 0.8–1.0×1.2–1.3 mm. in cross section. Microcorallites well developed in rentrant spaces where two macrocorallites join, and 0.2×0.3 mm. in cross section. Their visceral chambers almost square. Wall about 0.1 mm. in thickness, with no septal spinules. Tabulae in macrocorallites thin, complete and horizontal or slightly curved; 2 to 3 distributed in one millimeter in longitudinal section. Microcorallites tabulated closer than the preceding, 4–5 in one millimeter, with also thin, complete, horizontal tabulae (Plate IX, Figure 3). Wall surface of corallite tubes almost smooth; feeble corrugations visible in some parts (Plate IX, Figure 4).

Remarks:—This is characterized by its large corallum with small eye-shaped macrocorallite section. *Halysites süssmilchi* ETHERIDGE (1904) from the Gotlandian Bed **d** in the Spring Creek, Barton Co., Ashburnham, New South Wales, is almost the same as the Japanese form in various respects. Their slight differeces are tabled below:

	Australian form	Japanese form
corallum	sub-pyriform, radiate from a common base	almost parallel growth of corallites
chain	5–25 macrocorallites	5–9 macrocorallites
wall surface	coarsely striated	feebly corrugated

The differences seem to be attributed to the evironments of their habitats and bear no specific value.

Occurrence:—G_2 sandy limestone at the northwestern side of the Yokokura-yama (loc. 4b). With *Falsicatenipora shikokuensis*.

Repository:—PCa 7272～4.

Halysites tenuis, sp. nov.

Plate IX, Figures 5, 6; Plate X, Figure 1.

Description:—Corallum massive, medium in size, 8×10×3 cm. (imperfect specimen) at the largest. Fenestrules irregular in outline with meandering chains of corallites (Plate X, Figure 1), measuring 2.5×3 mm., 2×6 mm., 4×5 mm., 2.5×10 mm., and so on. A chain on one side of a fenestrule composed of 2, 3 or 5 macrocorallites, 10 at the maximum and commonly 3 to 6. Macrocorallites rectangular in transverse section, 0.7×0.8–0.9 mm. in mean size. Visceral chambers rounded or oval in shape since corallite walls are thickened at the ends of macrocorallites. Chain of corallites very slender, often curved in cross-section, and so little constricted at the junction between two macrocorallites that it appears almost even (Plate IX, Figure 5). Microcorallites well developed, rectangular in shape, 0.2×0.3 mm. in mean size. Mesocorallites large and depressed hexagonal in shape. Walls rather thick, 0.12–0.15 mm., and attain 0.2 mm. at the junctions of corallites. Surface of epitheca unknown. Septal spinules not visible. Tabulae thick, complete, horizontal, 0.4 to 0.5 mm. apart from one another in macrocorallites and 0.3 mm. apart in microcorallites.

Remarks:—Its small corallite size with slender outline of fenestrules in transverse section is so distinctive that it separates readily from other species. *Schedohalysites kitakamiensis* (SUGIYAMA) also have slender appearance, but it has larger corallites than the present form and lacks microcorallites in some parts of a corallum. The latter is provided with well developed microcorallites between the macrocorallites which have rounded visceral chambers in cross section. *Halysites elongatus* Yü from the Middle Gotlandian limestone at Chiu-chuan, Kansu Province, Northwest China also shows some resemblances in the fenestrule shape, but visceral chamber of its macrocorallite is larger and less rounded in transverse section.

Occurrence:—Lower Upper Gotlandian G_3 limestone at the Gion-yama (loc. 11).

Repository:—Holotype PCa 7275.

Halysites bellulus, sp. nov.

Plate X, Figures 2–4.

Description:—A little imperfect corallum was obtained. It is probably massive or platy in shape, 5×5×ca. 1 cm. though the upper part is gone by weathring. Fenestrules mostly uniform and pentagonal or hexagonal in outline, 2.5×2.5 mm., 3×3 mm., 2×5 mm., and so on. Chain composed of 1 or 2 generally and rarely 4 macrocorallites. Macrocorallites long oval in transverse section, 0.7×1.0 mm. in mean size; chain moniliform and constricted at junction where exists a microcorallite. Surface of epitheca unknown. Microcorallites rectangular in transverse outline, 0.1–0.2×0.3 mm. in size. Mesocorallites well developed in places where 3 or 4 macrocorallites are met with, and triangular or depressed hexagonal in shape. Corallite wall rather thin, 0.08 to 0.1 mm. in thickness. Septal spinules absent. Tabulae complete, horizontal, thin; their interval about 0.5 mm. in macrocorallites and 0.3 mm. in micro- and mesocorallites.

Remarks:—The slender and beautifully oval cross section of macrocorallite is quite distinctive for the species. The writer is aware no allied species.

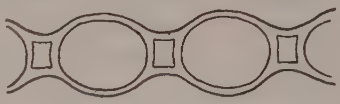
Occurrence:—Limestone of G_3 at the Gion-yama (loc. 11).

Repository:—Holotype PCa 7276.

Halysites ? sp. indet.

Text-figure 3.

Description:—Only a small fragment of probably a juvenile corallum kept in sandy shall is obtained. It is composed of a few chains without fenestrules. Macrocorallites almost rounded, about 0.75 mm. in diameter; visceral chambers also rounded in cross section. Microcorallites quadrangular, located at reentrant places of the chain. Corallite walls thin, about 0.1 mm., for only an epitheca is preserved; surface striated finely and transversely. Tabulae about 0.3 mm. apart from one another in macrocorallites, complete, straight or slightly curved. Septal spinules invisible.



Text-figure 3. An incomplete chain of *Halysites* ? sp. indet. showing the rounded macrocorallites and the microcorallites in the reentrant places. ×ca. 13

Remarks:—This specimen does not allow any exact comparison. The pretty rounded small macrocorallites and existence of microcorallites of this form suggest its similarity to *Acanthohalysites pycnoblastoides*. But the latter form has fenestrules oval, round, quadrangular and polygonal and occasionally irregular in shape, while the former shows only a few incomplete chains with 2 or 3 macrocorallites, probably because the specimen is a fragment of a juvenile corallum. ETHERIDGE's description of *A. pycnoblastoides* applies to this specimen except for the slightly larger macrocorallites and indistinct septal spinules which are due to unfavourable preservation of this specimen. *A. gamboolicus* well agrees with this form in the size of macrocorallites, but its wall is thick. *Halysites catenularius*, *H. agglomeratus* and *H. labyrinthicus* are also similar to this in the corallite shape, but the dimensions are pretty largar in them than in this form.

Occurrence: —Middle ? Gotlandian G_2 at the western foot of the Gion-yama (loc. 11). The specimen was procured from the sandy shale together with *Falsicatenipora shikokuensis* and *Encrinurus* sp.

Repository:—PCa 7278.

Incertae Sedis

"*Halysites*" ? sp. indet. SUGIYAMA, 1940

Halysites sp. indet. SUGIYAMA. 1940, *Sci. Rep. Tôhoku Imp. Univ., Second Ser. (Geol.), Vol. 21, No. 2*, p. 131, pl XXVIII (XVI), fig. 9.

The original description is read as follows:—

A part of a chain, composed of four corallites, about 20 mm. in length, more or less bending, and showing distinct catenated structure. Corallites large, up to 5 mm. in length and 3.5 mm. in the broadest part, somewhat subquadratic in outline. Tubules (microcorallites and mesocorallites in this paper) quite absent. Walls as broad as those of junctions, 0.5 mm. thick. Septa quite absent.

Remarks:—This form is represented by a thin section in the collection of the Tôhoku University. SUGIYAMA hesitated to create a new species because of the

insufficient material. This form is, however, as above quoted, devoid of septal spinules and microcorallites. Namely, this is a species of *Quepora*. SUGIYAMA noticed its great dimension. Really no species is known in *Quepora* whose corallite is so large. Judging from SUGIYAMA's plate the preservation of the specimen is so poor to warrant its being a chain coral. The type specimen was lost.

Type Locality:—*Halysites*-limestone at Kusayami-zawa, southern foot of the Takainari-yama (loc. K). Thin section only.

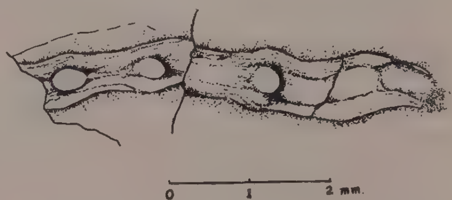
"*Halysites*"? sp. SUGIYAMA, 1944

Text-figure 4.

Halysites? sp. SUGIYAMA, 1944, *Tôkyô Bunrika-Daigaku, Geol. Min. Rep., No. 1*, p. 47, text-fig.

The original description in Japanese is translated here into English as follows:—

A cross section of a part of a corallum is at hand. It comprises 4–5 corallites. Its preservation is too poor to confirm its *Halysites* nature. There is a question whether it is kind of Bryozoa.



Text-figure 4. "*Halysites*"? sp. Reproduced from SUGIYAMA (1944, p. 47).

Remarks:—The specimen was lost during the World War II. Judging from the text-figure, it looks very close to some auloporoid corals in the widely spaced calices and the mode of the catenation.

Type Locality:—Imose-limestone, Imose (loc. 3). Probably from G_3.

V. Descriptions of Chinese and Korean Specimens

(A) Chinese species

Genus *Acanthohalysites* HAMADA, 1957

Acanthohalysites pycnoblastoides yabei, subsp. nov.

Halysites pycnoblastoides, YABE, 1915 (non ETHERIDGE, 1904), *Sci. Rep. Tôhoku Imp. Univ., Second Ser. (Geol.), Vol. 4, No. 1*, pp. 36, 37, pl. IX (V), figs. 3, 4.

Halysites pycnoblastoides, YABE and HAYASAKA, 1915, *Jour. Geol. Soc. Tôkyô, Vol. 22*, p. 79.

Halysites pycnoblastoides, YABE and HAYASAKA, 1920, *Geogr. Res. in China (1911–1915). Report, Vol. 3*, pp. 84, 85, pl. VII, figs. 3a, b.

The original description in Germany was translated into English by YABE and HAYASAKA (1915, 1920) as quoted below.

Corallum pyriform, small, 30 mm. high and 15 mm. wide; fenestrules somewhat irregularly polygonal rnd unequal in size; one side of the fenestrules composed of 1–11 corallites (macrocorallites in this paper) together with the corresponding number of the interstitial tubes (microcorallites); the average width of the fenestrules is 15 mm. Corallites (macrocorallites) oval in cross section, 1.8×1.5 mm. large, traversed by numerous tabulae which are complete and concave upwards; there are 8–9 tabulae in a space of 5 mm. Septal spines well developed in the corallites, always 12 in number, directed obliquely upwards; rather long, but not so long as to form a pseudocolumella at the center of the corallites. Interstitial tubes well developed, regularly intercalated between the corallite; those at the junction of three corallites (mesocorallites) are especially large, unequally six-sided, while the others are smaller (0.5×0.3 mm.), rectangular and elongate at right angle to

the chain of the corallites. Tabulae in the interstitial tubes horizontal, slightly less than twice as many as those in the corallites.

Remarks:—After YABE described the Chinese specimen in 1915, YABE and HAYASAKA (1915, 1920) noticed certain differences of the Chinese form from the Australian species. For instance, the corallites are more rounded in the former than in the latter. The differences were, however, not taken for specific or even varietal value.

In examining the topotype specimens kept in the Geological and Paleontological Institute of Tôhoku University, the writer convinced the Chinese form is distinguishable from the Australian in the subspecific rank at least. The distinction is as follows:—

1) Macrocorallite size is 1×1.5 mm. in transverse section in the Australian form, but 1.5×1.8 mm. in the Chinese one.
2) Corallum is as small as 15×30 mm. in the Chinese form, but much larger and 6×10 inches in the Australian. By this difference YABE has once taken the Chinese specimen for a juvenile stock of the Australian species (1915). The explanation, however, contradicts to the fact macrocorallite section is larger in the Chinese form than in the Australian one while the corallum size is smaller in the former than in the latter.

The Chinese form quite agrees with the Australian *A. pycnoblastoides* in other characters especially in the well rounded oval macrocorallite section. Tabulation of the Chinese specimens in the Tôhoku University varies in its spacing from 0.5 to 0.8 mm. The tabulae are slightly concave or horizontal and complete in the original species, although YABE's specimen (1915) reveals pathological injury in the tabulation.

It is noteworthy that the Chinese specimens were collected from the Gotlandian shale instead of limestone. The subspecific name *yabei* is given in honour of Em. Prof. Hisakatstu YABE of the Tôhoku University of Sendai.

Occurrence:—Lo-ling-po, north of No-lu-ping, Hu-chi, Hsingshan-hsin, Province of Hu-peh, Central China. Middle Gotlandian.

Repository:—Ia (section number), Geological and Paleontological Institute, Tôhoku University of Sendai, Miyagi Prefecture.

(B) Korean species

Genus *Quepora* SINCLAIR, 1955

Quepora cfr. *sindoensis* (OZAKI),

Plate VIII, Figures 6, 7.

Cf. *Halysites sindoensis* OZAKI, 1934, in SHIMIZU, OZAKI and OBATA, *Jour. Shanghai Sci. Inst., Ser. 2, Vol. 1*, p. 77, pl. XVI, figs. 5–7; pl. XVII, figs. 2, 3.

Catenipora sindoensis, BUEHLER, 1955, *Peabody Mus. Nat. Hist., Bull., No. 8*, p. 61.

The original description of *Halysites sindoensis* runs as follows:—

Species easily distinguishable from allied form owing to one side of its fenestrules being almost invariably composed of a single corallite, although not always joined to another at the restricted edges.

Fenestrules rather regularly polygonal, but differ in size, largest one composed of 8 corallites, smallest of 5. In my specimen, ornamentation of surface of walls not observable owing to recrystallization. Corallites oval in cross section, about 1×1.5 mm., traversed by numerous thin tabulae regularly distributed and concave upwards; 14 or more tabulae in

space of 5 mm. Wall of corallites thicker than tabulae. No septal spine traceable. Interstitial tube (microcorallites in this paper) absent.

Dimensions:—

Size of corallite	ca. 1×1.5 mm.
Largest width of fenestrule	ca. 4 mm.
Smallest width of fenestrule	ca. 1 mm.
Number of tabulae per 5 mm.	14.

Description of the Present Specimen:—A small fragment of the corallum is preserved in the Geological Institute, University of Tôkyô. The specimen is composed of a few, small fenestrules so much silicified secondarily that they are etched out on rock surface. Corallite small, 0.8 mm. wide and 1.2 or 1.3 mm. in length, oval in cross section. One side of fenestrules consists of one or two corallites which join each other without strong constriction. Walls thin, about 0.1 mm. in thickness; intercorallite walls also in the same dimension; outer surface feebly striated transversely. Tabulae thin, 6 or 7 in every 4 mm. in longitudinal section. Septal spinules, mesocorallites and micorocralites absent.

Remarks:—The present specimen was collected by Prof. KOBAYASHI from the type locality of *H. sindoensis* in 1935. The writer's observation almost coincides with the description of *H. sindoensis* OZAKI except for its slightly smaller size of the corallites. *Quepora sapporiensis* (OZAKI) is also much close to this form. BUEHLER (1955, p. 61) stated that further sampling may show that they are varieties of one species. Unfortunately their type specimens are destroyed during the last war time. The present specimen affords the intermediate size between these two species. It seems there is no other difference among them.

The ratios of length to width of the corallites of these forms are as follows:

	Q. sindoensis	Present specimen	*Q. sapporiensis*
size of corallite	1.0×1.5 mm.	0.8×1.2–1.3 mm.	0.7×1.0 mm.
ratio length/wide	1.5	1.5–1.6	1.4

Thus, the present form is probably referable to *Quepora sindoensis* (OZAKI), if there is no intermediate forms between *Q. sapporiensis* and *Q. sindoensis*.

SHIMIZU, OZAKI and OBATA (1934) reported the fossils to occur in the Gotlandian deposits. Subsequently KOBAYASHI (1935) proved that they are derived fossils contained in the limestone boulders of the basal conglomerate of the Mesozic Daidô series. It is noteworthy that some Cambrian and Ordovician fossils were procured by him in the conglomerate.

OZAKI described *Halysites escharoides* FISCHER-BENZON, *H. sindoensis* and *H. sapporiensis* from this Ken-Niho limestone conglomerate, and considered them to be the Gotlandian forms. Most species of *Quepora* are, however, found from the Ordovician strata (HAMADA, 1957b, c). It seems that there is no possitive element of the Gotlandian age among the Ken-Niho conglomerate fauna. Judging from the assemblage, the Halysitidae in the fauna must be Upper Ordovician if not Lowest Gotlandian.

OZAKI's *Halysites escharoides* FISCHER-BENZON (1934, pl. XVI, figs. 3, 4; pl. XVII, fig. 1 ; pl. XVIII, figs. 1, 2) is not *H. escharoides* but a form of *Quepora* because it lacks spinules as WEISSERMEL (1935, p. 19) pointed out. A new name *Quepora ozakii* is proposed here for this new species. This form is quite isolated from the known species of *Quepora*. It is an interesting fact that the chain

corals found in the Ken-Niho limestone conglomerate are all quite exotic for the Asia-Australian halysitid faunas.

Occurrence:—In the basal conglomerate of the Older Mesozoic Daidô series, 2 km. northeast of Kyŏmip'o (兼二浦, Ken-Niho), Songnim-myŏn (松林面, Shôrin-men), Hwangju-kun (黃州郡, Kôshû-gun), Hwanghae-do (黃海道, Kôkai-dô), Korea.

Repository:—PCa 7277.

VI. Notes on Asiatic and Australian Halysitidae

Some 40 species of the Halysitidae have been reported from the Gotlandian rocks in Asia and Australia. Among them the Australian ones are well studied by ETHERIDGE jun. (1904) and HILL (1954), and northern Siberian ones by TCHERNYCHEV (1937). Many others were reported from various localities by some authors. Here are described 10 forms from Japan.

The writer (1956, p. 134; 57, p. 401; 57, p. 419) pointed out the predominance of slender forms and the Schedohalysitinae to be the characteristics of Gotlandian coral faunas of Asia and Australia. Tentative generic identification is given in the following list of the species which is made on the basis of their descriptions and figures except for the Japanese and a few Chinese and Korean forms. Due to the lack of recent references no comment can be given on the Central Siberian chain corals. Therefore, they are still in old fashion.

Australia:
- *Falsicatenipora chillagoensis* (ETHERIDGE), 1904
- *F. hillae* (HAMADA), 1957
- *F.* sp. indet. by HILL, 1954
- *Schedohalysites orthopteroides* (ETHERIDGE), 1904
- *S. yarrangobillyensis* HAMADA, 1957
- *Halysites cratus* ETHERIDGE, 1904
- *H. lithostrotonoides* ETHERIDGE, 1904
- *H. süssmilchi* ETHERIDGE, 1904
- *Acanthohalysites australis* (ETHERIDGE), 1904
- *A. gamboolicus* (ETHERIDGE), 1904
- *A. peristephesicus* (ETHERIDGE), 1904
- *A. pycnoblastoides* (ETHERIDGE), 1904
- *A. kuraokensis*, sp. nov.
- *Densoporites brevicatenatus* (HILL), 1954

Tasmania:
- *Falsicatenipora chillagoensis* (ETHERIDGE), 1904

New Guinea:
- *Catenipora ? wallichi* (COWPER REED), 1912

Himalayas:
- *Catenipora ? wallichi* (COWPER REED), 1912
- *Schedohalysites kanaurensis* (COWPER REED), 1912
- "*Halysites*" sp. by COWPER REED, 1912

Yunnan:
- "*Halysites*" sp. by SUN and SZETU, 1947

Central China
- *Schedohalysites hupehensis* (GRABAU), 1925
- *Halysites cratus* ETHERIDGE, 1904
- *Acanthohalysites pycnoblastoides yabei*, subsp. nov.
- "*Halysites catenularius* (LINNAEUS), 1767"

Northwestern China:
Halysites elongatus YÜ, 1956

Korea (in the Mesozoic Ken-Niho conglomerate):
Quepora sapporiensis (OZAKI), 1934
Q. sindoensis (OZAKI), 1934
Q. cfr. *sindoensis* (OZAKI), 1934, by HAMADA, 1958
Q. ozakii, sp. nov.

Japan:
Catenipora ? sp. indet.
Falsicatenipora japonica (SUGIYAMA), 1940
F. shikokuensis NODA and HAMADA, sp. nov.
Schedohalysites kitakamiensis (SUGIYAMA), 1940
Acanthohalysites kuraokensis, sp. nov.
Halysites cratus ETHERIDGE, 1904
H. süssmilchi ETHERIDGE, 1904
H. tenuis, sp. nov.
H. bellulus, sp. nov.
H. ? sp. indet.
"*Halysites*" ? sp. indet. by SUGIYAMA, 1940
"*H.*" ? sp. by SUGIYAMA, 1944

Siberia:
Steinige Tunguska:
Catenipora escharoides LAMARCK, 1816*
Halysites catenularius (LINNAEUS), 1767*
H. catenularius (LINNAEUS), 1767

Kotelny Island:
Quepora parallela (SCHMIDT), 1861
Halysites catenularius (LINNAEUS), 1767
H. ? *keyserlingi* TOLL, 1889

Olenek:
Catenipora escharoides LAMARCK, 1816

Khatanga:
Halysites catenularius (LINNAEUS), 1767

Kolyma River basin:
Quepora sindoensis (OZAKI), 1934

Verkhoiansk between Aldan and Indigirka:
Halysites sp.

Tarbagatai:
Catenipora escharoides LAMARCK, 1816
Halysites sp. indet.

Western Kwenlun:
Halysites sp. indet.

Alai:
Halysites sp. indet.

Yaigatch, Novaya Zemlya, Severnaya Zemlya, Taimyr:
Catenipora minima (TCHERNYCHEV), 1937
Schedohalysites kuliki (TCHERNYCHEV), 1938
S. pseudoorthopteroides (TCHERNYCHEV), 1937
Halysites latus (TCHERNYCHEV), 1937
H. taimyricus (TCHERNYCHEV), 1937
H. ? *keyserlingi* TOLL, 1899
Acanthohalysites borealis (TCHERNYCHEV), 1937

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* From the Ordovician rocks.

Russian Altai and North Siberia:
Quepora parallela (SCHMIDT), 1861
Catenipora gothlandica (YABE), 1915

As above listed, there are only a few Ordovician forms in Central Siberia, and all others are in the Gotlandian strata. This is a remarkable characteristic of the area in comparison with North America and Europe where many Ordovician chain corals are known. A small number of species are common between the Asiatic-Australian and European-North American areas except for "*Halysites catenularius*" and "*Catenipora escharoides*" in old references.

Thus, insofar as the Halysitidae are concerned, Asia and Australia evidently constitute a distinct faunal province. The writer, therefore, proposes a name, "Asia-Australian Sea", for the Gotlandian sea of the province. The presence of closely related forms of the Schedohalysitinae and the Halysitinae and the predominance of slender chain corals are two characteristics of the province.

The Asia-Australian Sea was, however, probably connected with European Sea through the Himalaya and Tsingling geosynclines in the Gotlandian period. The early Gotlandian fauna from Spiti, Central Himalaya has many affinities to the European one as GRABAU stated (1923–24). In 1953, GILL pointed out a close faunal connection between the Australian and the North African-European areas along the Tethys Seaway and a less successful connection with the North American area during the Lower Devonian time. KOBAYASHI (1955) recognized the sea connection in the early Ordovician time from Europe to Australasia and Eastern Asia through the Himalayan geosyncline, and said that so far as the Ordovician trilobites are concerned, the Australasian fauna is distinct from the North American one, but there is *Carolinites*. KOBAYASHI and IGÔ (1956) also noted that the Devonian trilobites *Cheirurus* (*Crotalocephalus*) from the Central Japan reveals the alliance of the Japanese fauna with those of Central Asia, Australia and Europe. It is noteworthy that no *Crotalocephalus* has so far been found from Americas. Recently, KOBAYASHI (1957) discussed the Devonian trilobites *Dechenella* (*Dechenella*) and *Scutellum* (*Thysanopeltella*) from the Kitakami mountains, Northeast Japan, emphasizing the faunal connection between Japan and Europe. The latter is unknown from North America and the former is, though occurs in North America, not so well developed as in Europe.

As above mentioned, it is interesting to see that the close Asia-Australian faunal connection persists from the Ordovician to the Devonian through the Gotlandian period.

VII. Summary

The Gotlandian stratigraphy of the outer zone of Southwest Japan is made out on the bases of the halysitid fauna and lithology, and its tentative correlation with the deposits in the Kitakami mountains, Northeast Japan is attempted. The limestone of the bed G_3 is remarkably characterized by the predominance of *Schedohalysites kitakamiensis* in the fauna, and may be Lower Ludlovian in age. *Falsicatenipora* is a new genus of the Schedohalysitinae having mesocorallites at the corner of the corallite chains but no microcorallites.

The terms "macrocorallite", "mesocorallite" and "microcorallite" are redefined, and applied to three kinds of the zooids of the Halysitidae.

Some ten forms of the chain corals are recognized in the Gotlandian deposits of Japan from the beds G_2 and G_3. They are tabulated as follows:—

Locs. & Beds / Species	G3															G2		
	K	1	2	3	4 a	5	6	7	8 a	8 b	9	10	11	12 a	12 b	4 b	10	11
Catenipora ? sp.																		×
Falsicatenipora japonica	×			×	×		×											
F. shikokuensis																×	?	×
Schedohalysites kitakamiensis	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×			
Acanthohalysites kuraokensis																		×
Halysites cratus															×			
H. süssmilchi																×		
H. tenuis													×					
H. bellulus													×					
H. ? sp. indet.																		×
"*H.*" ? sp. indet.	×																	
"*H.*" ? sp.				×														

A new Chinese subspecies *Acanthohalysites pycnoblastoides yabei* and a Korean primitive species *Quepora* cfr. *sindoensis* are also described. *Q. ozakii* is a new name for new species once described as *Halysites escharoides* by Ozaki in 1934.

Some 40 forms of chain corals from Asia and Australia are listed with tentative generic assignment. The characteristics of the Gotlandian Asia-Australian Sea lie in the predominance of slender form of chain corals and Schedohalysitinae by which it is distinct from other areas, especially from Americas. The sea, however, seems to be existed not only in the Gotlandian but in the Ordovician and Devonian periods as discussed by several authors.

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T. Hamada

Japanese Halysitidae

Plate VI

Explanation of Plate VI

Falsicatenipora japonica (SUGIYAMA) .... p. 99

Fig. 1. A cross section showing a mesocorallites. ×5
Loc. Gion-yama, Kuraoka, Gokase-machi, Nishiusuki-gun, Miyazaki Prefecture (loc. 11). Bed G_3. Reg. No. PCa 7251.

Fig. 2. Another cross section. ×6
Loc. Ditto. Reg. No. PCa 7252.

Schedohalysites kitakamiensis (SUGIYAMA) p.100

Fig. 3. A longitudinal section showing expansion of a corallum. ×3
Loc. Ditto. Bed G_3. Reg. No. PCa 7260.

Falsicatenipora shikokuensis NODA and HAMADA, sp. nov. .... p. 99

Fig. 4. A cross section showing small fenestrules and mesocorallites. (A part of the specimen shown in Plate VII, Figure 6). ×5
Loc. Northwestern side of Yokokura-yama, Ochi-machi, Takaoka-gun, Kôchi Prefecture (loc. 4b). Bed G_2. Reg. No. PCa 7253 (Holotype).

Fig. 5. A longitudinal section of the same specimen showing the shape of calyces. ×5

Catenipora ? sp. indet. .... p. 97

Fig. 6. Basal view of a weathered corallum showing the irregular fenestrules. ×2
Loc. Western foot of Gion-yama, Kuraoka, Gokase-machi, Nishiusuki-gun, Miyazaki Prefecture (loc. 11). Bed G_2. Reg. No. PCa 7250.


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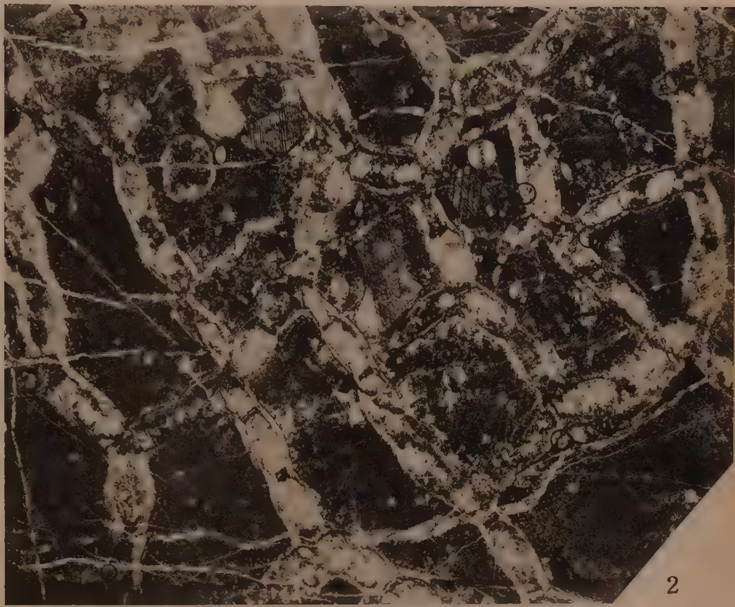
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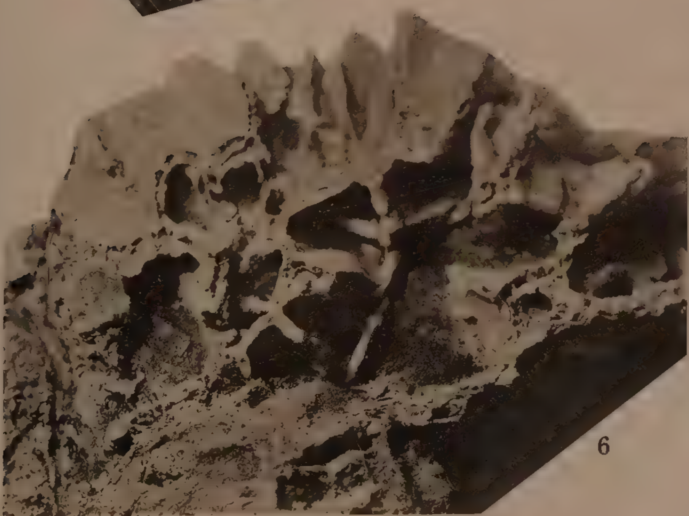
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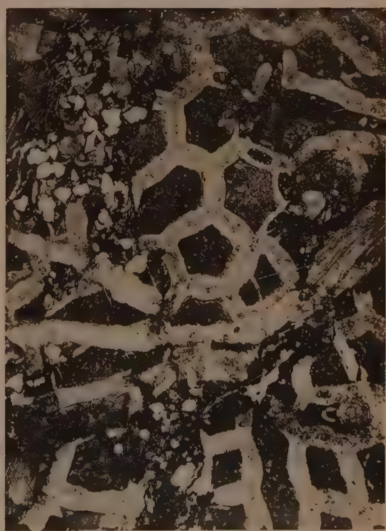


Photo. by UEKI

T. Hamada

Japanese Halysitidae

Plate VII

Explanation of Plate VII

Falsicatenipora shikokuensis NODA and HAMADA, sp. nov. .... p. 99

Fig. 1. A cross section showing the small fenestrules. ×6

Loc. Southwestern foot of Gion-yama, Kuraoka, Gokase-machi, Nishiusuki-gun, Miyazaki Prefecture (in a limestone boulder). Reg. No. PCa 7255.

Fig. 2. Weathered surface of a corallum. ×4

Loc. Western foot of Gion-yama, Kuraoka, Gokase-machi, Nishiusuki-gun, Miyazaki Prefecture (loc. 11). Bed G_2. Reg. No. PCa 7256.

Fig. 3. Side view of the same specimen. ×4

Fig. 4. Top view of a loose specimen. ×5

Loc. Ditto. Reg. No. PCa 7257.

Fig. 5. Side view of another corallum showing the virgation of corallites, tabulation and faint striation on the surface of corallite tubes. ×4

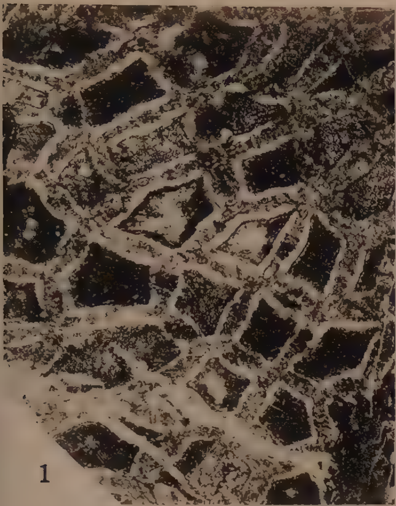
Loc. Ditto. Reg. No. PCa 7258.

Fig. 6. Polished specimen showing the aggregation of small coralla. Note the hemispherical shape of the corallum. ×1.43

Loc. Northwestern side of Yokokura-yama, Ochi-machi, Takaoka-gun, Kôchi Prefecture (loc. 4b). Bed G_2. Reg. No. PCa 7253 (Holotype).

Fig. 7. A longitudinal section showing the tabulation in mesocorallites and macrocorallites. ×5

Reg. No. PCa 7253 (Holotype).



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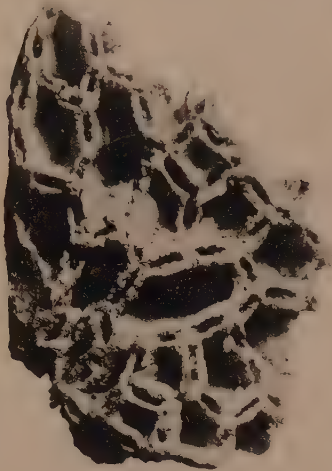

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Photo. by UEKI

T. HAMADA

Japanese Halysitidae

Plate VIII

Explanation of Plate VIII

Acanthohalysites kuraokensis HAMADA, sp. nov. .... p. 101

Fig. 1. A cross section showing the beautifully eye-shaped macrocorallites and septal spinules. ×6

Loc. Western foot of Gion-yama, Kuraoka, Gokase-machi, Nishiusuki-gun, Miyazaki Prefecture (loc. 11). Bed G_2. Reg. No. PCa 7269 (Holotype).

Fig. 2. A longitudinal section of the same specimen showing the tabulation in macrocorallites and microcorallites. ×5

Fig. 3. Weathered surface of the same specimen showing the shape of macrocorallites. ×6

Schedohalysites kitakamiensis (SUGIYAMA) p.100

Fig. 4. A cross section showing rather thick walls and their thickening at the junctions of macrocorallites. ×6

Loc. Southwest of Mitaki-yama, Kurosegawa-mura, Higashiuwa-gun, Ehime Prefecture (loc. 8b). Bed G_3. Reg. No. PCa 7261.

Fig. 5. Another cross section.

Loc. Northeast of Kamifukami, Shimomatsukuma-mura, Yatsushiro-gun, Kumamoto Prefecture (loc. 12b). Bed G_3. Reg. No. PCa 7262.

Quepora cfr. *sindoensis* (OZAKI) p.106

Fig. 6. A cross section of a small corallum. ×4.5

Loc. Ken-Niho conglomerate (Mesozoic Daidô series), 2 km. northeast of Kyŏmip'o, Northwest Korea.

Coll. by T. KOBAYASHI. Reg. No. PCa 7277.

Fig. 7. A longitudinal section of the same specimen showing rather thin tabulae. ×4.5


1


2

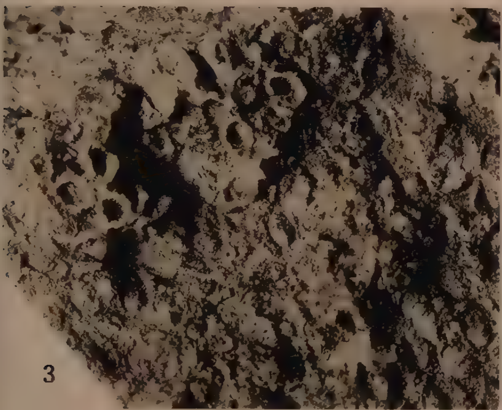
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Photo. by UEKI

T. HAMADA

Japanese Halysitidae

Plate IX

Explanation of Plate IX

Halysites süssmilchi ETHERIDGE p.102

Fig. 1. A cross section of a large corallum showing the meandering or labyrinthine fenestrules. ×3

Loc. Northwestern side of Yokokura-yama, Ochi-machi, Takaoka-gun, Kôchi Prefecture (loc. 4b). Bed G_2. Reg. No. PCa 7272.

Fig. 2. A part of Fig. 1 showing the oval macrocorallite shape. ×5

Fig. 3. A longitudinal section of the same specimen showing the parallel growth of corallite tubes and their tabulation. ×5

Fig. 4. A side view of a part of a corallum showing the wall surface. ×3

Reg. No. PCa 7273.

Halysites tenuis HAMADA, sp. nov. p.103

Fig. 5. A cross section showing the rounded macrocorallite shape and microcorallites. Note the slender outline of corallite chains. ×6

Loc. Gion-yama, Kuraoka, Gokase-machi, Nishiusuki-gun, Miyazaki Prefecture (loc. 11). Bed G_3.

Reg. No. PCa 7275 (Holotype).

Fig. 6. A longitudinal section of the same specimen. ×6

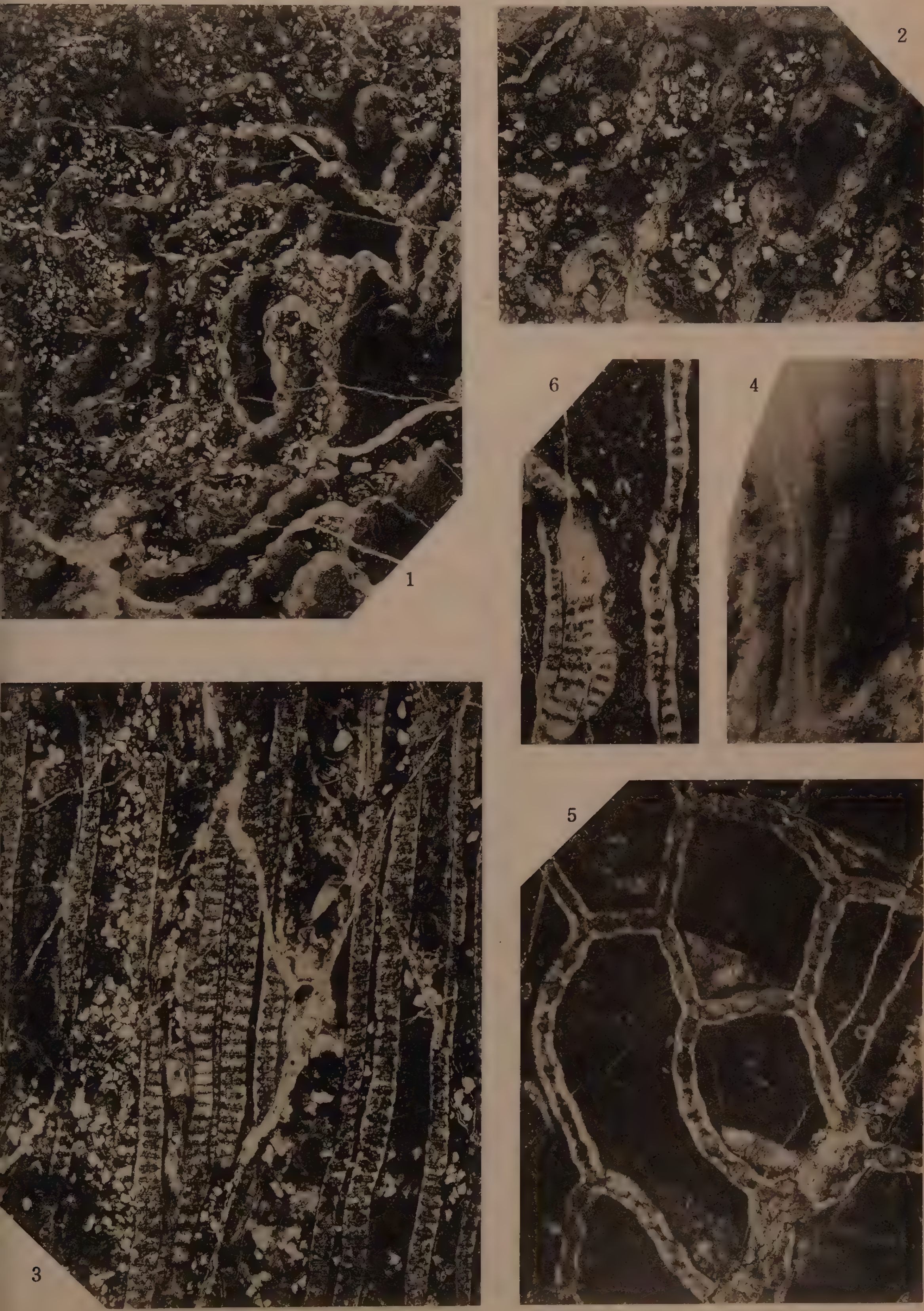


Photo. by UEKI

T. Hamada

Japanese Halysitidae

Plate X

Explanation of Plate X

Halysites tenuis HAMADA, sp. nov. p.103

Fig. 1. Another cross section of the holotype showing the irregularly elongated fenestrules. ×3.

Halysites bellulus HAMADA, sp. nov. p.103

Fig. 2. A cross section showing the slender and oval macrocorallite shape and rather small fenestrules. ×6

Loc. Gion-yama, Kuraoka, Gokase-machi, Nishiusuki-gun, Miyazaki Prefecture (loc. 11). Bed G_3.

Reg. No. PCa 7276 (Holotype).

Fig. 3. A longitudinal section of the same specimen showing the tabulation in macrocorallites and a mesocorallite. ×6

Fig. 4. A top view of weathered surface of a corallum of the holotype specimen showing the rather regular small fenestrules. ×2

Halysites cratus ETHERIDGE p.101

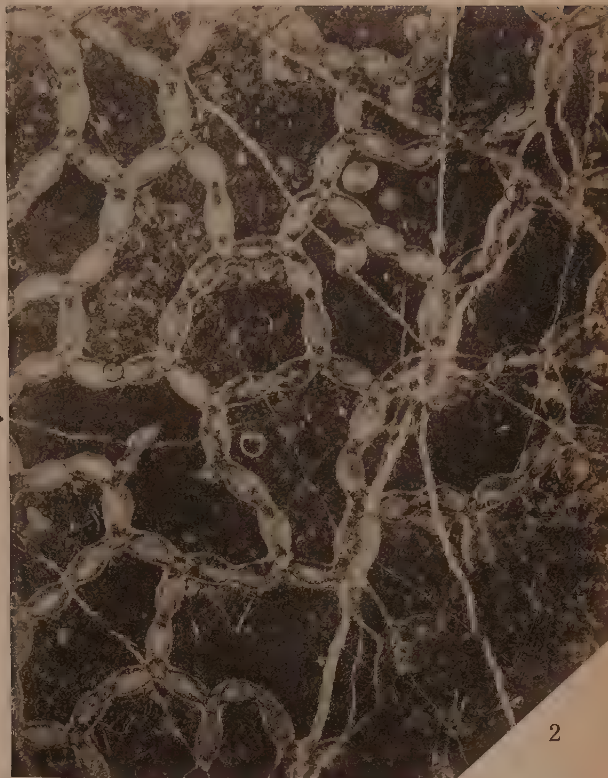
Fig. 5. A cross section of a part of a corallum showing the well developed microcorallites and mesocorallites between large, rounded macrocorallites. ×5

Loc. Northeast of Kamifukami, Fukami, Shimomatsukuma-mura, Yatsushiro-gun, Kumamoto Prefecture (loc. 12b). Bed G_3.

Reg. No. PCa 7271.

Figs. 6a, b. Cross sections of the same specimen (in the same thin section). ×5

1



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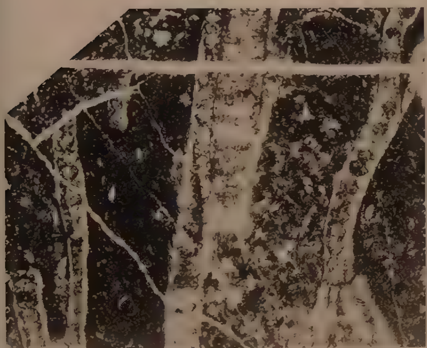

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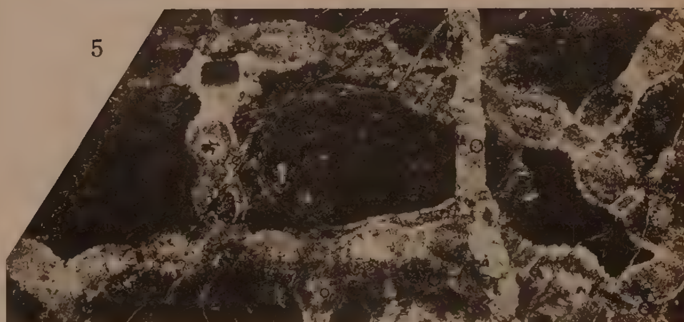

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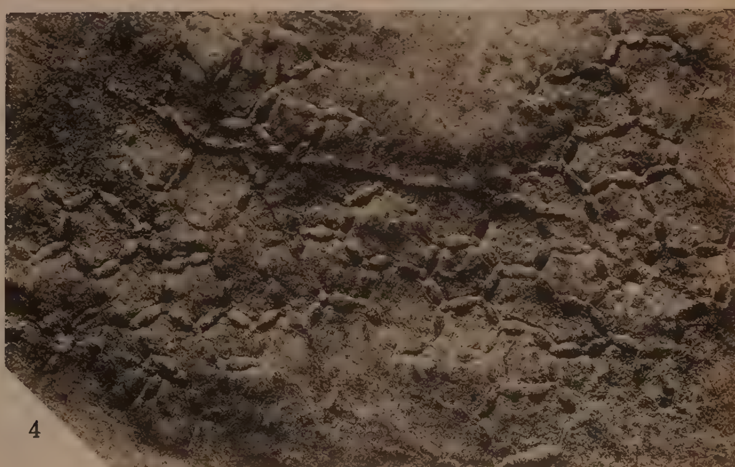
6a

6b



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TAXONOMIC NOTES ON CARDINIA WITH DESCRIPTION OF A NEW SPECIES FROM THE LIAS OF WESTERN JAPAN*

By

Itaru HAYAMI

With One Plate

In 1956, I collected several specimens belonging to a new species of *Cardinia* from the basal part of the lower Liassic Higashinagano formation of the Toyora group in Yamaguchi Prefecture, West Japan. The cardiniid occurs in a small fossil bank together with many other pelecypods including *Prosogyrotrigonia inouyei* (YEHARA), gastropods, an ammonite, a brachiopod, two hexacorals (*Chomatoseris cyclitoides* and an isastraeid) and a crinoid. MATSUMOTO and ONO (1947) reported *Rhacophyllites* (*Harpophylloceras*) sp. from this horizon and suggested Hettangian for the fauna.

Cardinia AGASSIZ has been regarded as an important pelecypod genus especially for Liassic stratigraphy and chronology. The genus shows quite variable outlines and ornamentations, but no attempt to divide the genus into groups of lower category has been done. On this occasion I discuss the taxonomy and morphological relationship among *Cardinia* and its related genera. As I could observe only a few foreign specimens besides Japanese ones, I do not here divide it into subgenera but into several groups which consist of morphologically intimate species.

Before discussion, I wish to express my sincere thanks to Prof. Teiichi KOBAYASHI of the University of Tokyo for his kind advices and encouragements, and also to Dr. Leslie R. Cox of the British Museum for his kind and instructive informations about this genus.

Taxonomic Notes on *Cardinia*

Since SOWERBY had described several species under the generic name of *Unio* in his Mineral Conchology, many Liassic species of *Cardinia* were reported in Western Europe by GOLDFUSS (1836), KOCH and DUNKER (1837), STUTCHBURY (1842), AGASSIZ (1843), D'ORBIGNY (1850), DUNKER (1851), CHAPUIS and DEWALQUE (1853), TERQUEM (1855), QUENSTEDT (1856), CHAPUIS (1858), MARTIN (1859), DUMORTIER (1867, 1869), TERQUEM and PIETTE (1868), COSSMANN (1904), JOLY (1908, 1936), TROEDSSON (1951) and some others, and several Rhaetic species by DITTMAR (1864), DUMORTIER (1864), LEVALLOIS (1865), PLÜCKER (1868), OOSTER (1869) and REYNOLDS and VAUGHAN (1904). So far as I am aware, the occurrence of *Cardinia* is restricted to the Rhaetic to Dogger in Europe, but in some other continents older forms were reported. McCOY (1847), SWALLOW (1858), WAAGEN (1881), STUCKENBERG (1898) and some others described several species** from the Permian

* Received June 9, 1958.

** Many Permian "*Cardinias*", which are omitted in my synoptic list, were referred to some other Palaeozoic suitable genera by BRANSON (1948, *Geol. Soc. America, Mem. 26*).

of Australia, North America, India and Russia. Their generic references are, however, not warranted, because their hinge and other principal characters are unknown or seemingly different from Mesozoic true *Cardinia*. It is, therefore, quite doubtful if such Palaeozoic species are actually ancestral to Mesozoic forms. Two undoubted species of *Cardinia* appeared at first in the Carnic of Japan (KOBAYASHI and ICHIKAWA, 1952a; ICHIKAWA, 1954; NAKAZAWA, 1955, 1956). In North America SMITH (1927) reported also a Carnic species. Other Triassic cardiniids occur in the Noric of Japan (KOBAYASHI and ICHIKAWA, 1952b), Upper Triassic of Northern Siberia and Elleresmereland (KITTL, 1907; VORONETZ, 1936, KIPARISOVA, 1937) and Rhaetic of New Zealand (MARWICK, 1953; FLEMING, 1957).

But *Cardinia* show as a whole an acmaic development in lower Liassic times. As shown in Table 1, lower Lias yields more than 80 species which occupy more than 70 percent of true cardiniids. In outside of Western Europe,

Table 1. Number of Species of *Cardinia* in each geological Stage.

Stage	Undoubted occurrence	Doubtful occurrence
Dogger	2	1
Upper Lias	6	0
Middle Lias	7	2
Lower Lias	88	0
Rhaetic	8	0
Noric	1	3
Carnic	2	2

Liassic *Cardinia* is distributed in Eastern Greenland (ROSENKRANTZ, 1934), Ferghana, Caucasus (PČELINCEV, 1937), Northern Siberia (VORONETZ, 1936), Japan, Indochina (MANSUY, 1914, 1919), Alberta (WARREN, 1932, Bajocian?), California (HYATT, 1894) and the southern Andes (JAWORSKI, 1915; FERUGLIO, 1934; LEANZA, 1942). A few species are found in the European Dogger, but none survived until Malm.

About 100 species hitherto described from the Upper Triassic and the lower half of Jurassic have actually a fairly persistent hinge-structure composed of a more or less obsolete cardinal (3b) and a pair of characteristic remote laterals (AI–III, PI–III), and should be included in one genus. Only a few species such as *Cardinia listeri* show complete obsolescence of the cardinal tooth and are slightly different in hinge aspect from normal ones. But it is not considered of generic importance. Musculature is of primitive heterodont type, also very persistent and composed of strongly impressed anisomyarian adductors, clear posterior pedal scar and entire pallial line. Ligament is subinternal and sunk profoundly between subvertical escutcheons, and the character makes it easy to distinguish *Cardinia* from Schizodont and more primitive Heterodont genera. However, the external aspect and ornamentation of *Cardinia* are quite variable, and the genus can be divided into several groups of lower category. Some of them may require subgeneric distinction, but I do not propose here new subgeneric names, because their differences and phylogenetical relationship must be further studied.

Chief criteria for the subdivision of *Cardinia* are considered to exist in shell-outline, umbonal position, ventral sinuation, development of lunule and surface-ornamentation. There is certain relationship among these characters: for instance, *Cardinia concinna* and its related species (i. e. *Cardinia* s. s.) with comparatively large and elongated shells do not show strong concentric ornamentation, while smaller and cuneiform species such as *Cardinia hybrida* are provided with deep lunule, very prosogyrous umbo and strong concentrics. In view of these characters most species of *Cardinia* can be classified into the following five groups.

1. *Concinna*-group (*Cardinia* s.s.) (Pl. XI, Figs. 12a–b)

Diagnosis:—Shell large, very elongated, usually twice or more as long as high, not strongly inflated; umbo more or less prosogyrous, lying very anteriorly, not projected anteriorly; surface smooth without any strong concentric ornaments, marked only with weak irregular lamellae and numerous fine growth-lines.

Distribution:—Noric (?), Rhaetic to middle Lias of Western Europe, Greenland, Ferghana, Northern Siberia and Indochina.

List of Species:—*Cardinia angustata* (?), *concinna*, *copides*, *elongata*, *eveni* (?), *fischeri* (?), *gigantea*, *hennocquii*, *infera*, *kullensis*, *lanceolata* (?), *philea*, *porrecta* (?), *scapha* and *secuiformis* (?).

2. *Crassissima*-group (Pl. XI, Figs. 13a–b)

Diagnosis:—Shell medium to large, ovate or subelliptical, not elongated, well inflated; test thick; umbo prosogyrous; lunule fairly deeply excavated below beak, sometimes folded; surface marked with concentric lamellae of variable strength, but lacks any strong ribs or imbrications.

Distribution:—Rhaetic to lower Dogger of Western Europe, Northern Siberia (?), South America (?) and Indochina (?).

List of Species:—*Cardinia acuminata*, *breoni*, *brevis*, *collenoti*, *contracta*, *crassissima*, *crassiuscula*, *deshayesi*, *desoudini*, *insignis*, *minor*, *moreana*, *obovata*, *ovum* (?), *quadrangularis*, *regularis*, *siberica* (?), *sinemuriensis*, *sublamellosa*, *subovalis*, *tas-aryensis* (?) and *trapezium*.

3. *Piriformis*-group (Pl. XI, Figs. 14a–b)

Diagnosis:—Shell medium to large, highly inequilateral, pyriform with a posteriorly rostrated part and distinct postero-ventral sinuation; test very thick; hinge-plate heavy with more or less tubercle-like lateral teeth: umbo slightly prosogyrous; surface marked only with weak growth-lamellae.

Distribution:—Lower Lias of Western Europe.

List of Species:—*Cardinia chillyensis*, *piriformis* and *plana*.

4. *Hybrida*-group (Pl. XI, Figs. 1–11, 15–17).

Diagnosis:—Shell small to large, only slightly inflated, not very elongated but more or less expanded postero-ventrally, often more or less cuneiform with slight ventral sinuation and anteriorly protruded prosogyrous umbo; test not very thick; lunule deep; surface marked with strong and often imbricated concentric lamellae.

Remarks:—*Hybrida*-group consists of the following three subgroups.

4a. *Hybrida*-subgroup (Pl. XI, Figs. 15a–b, 16) with small to medium size, cuneiform outline, distinct ventral sinuation, very prosogyrous and anteriorly protruded umbo, profoundly excavated lunule which is covered upwards with beak and vertically depressed, and strong concentric ribs whose interspaces are often striated by many fine secondaries or growth lines.

Distribution:—Rhaetic to middle Lias of Western Europe, Greenland and Northern Siberia.

List of Species:—*Cardinia abducta, amygdala, angustiplexa, aptycha, cuneata, depressa, dunkeri, gibba, gibbosula, hybrida, idalia, imbricata, itea, lamellosa, latiplexa, listeri, morisi, nilssoni, quadrata* and *sulcata*.

4b. *Toriyamai*-subgroup (Pl. XI, Figs. 1–11) with comparatively small size, more elliptical outline, less prominent and more posterior umbo and more strongly imbricated and widely spaced concentric lamellae with smooth or only faintly striated intervals than in the preceding subgroup.

Distribution:—Carnic to lower Lias of Western Europe, Northern Siberia, Arctic (?) and Japan.

List of Species:—*Cardinia elliptica, misawensis, ovalis, ovula* (?), *regularis* (in VORONETZ, 1936), *similis, toriyamai* and *triadica*.

4c. *Densestriata*-subgroup (Pl. XI, Fig. 17) with large size, similar outline to the preceding subgroup, obscure ventral sinuation, strong concentric ribs or lamellae whose intervals are striated by fine secondaries or growth-lamellae.

Distribution:—Middle to upper Lias of South America.

List of Species:—*Cardinia andium, densestriata*.

5. *Unioides*-group (Pl. XI, Fig. 18)

Diagnosis:—Shell medium to small, subequilateral, trigonal; ventral sinuation absent, umbo only slightly prosogyrous, lying submesially; surface lacks any strong concentric ornamentation.

Distribution:—Lower Lias of Western Europe.

List of Species:—*Cardinia cyprina, subaequilateralis, trigona* (?) and *unioides*.

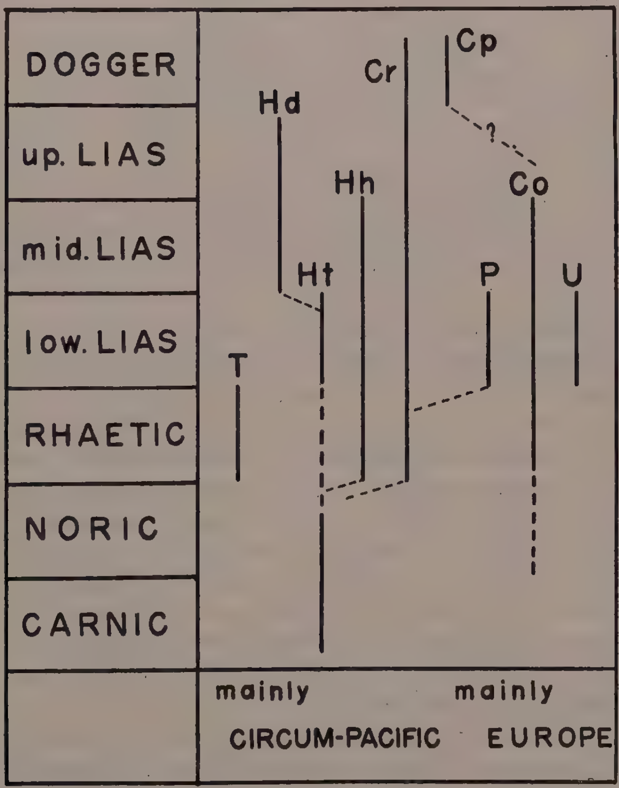
6. Other groups

Besides, it is presumed that there are several species of *Cardinia* belonging to other groups, such as *Cardinia attenuata, exigua, expansa, follini, ingelensis, oblonga* and *lucinaeformis*. MARWICK (1953) established *Torastarte* for a Rhaetic species from New Zealand and took it for a genus of the Astartidae. Subsequently FLEMING (1957) included it in the Cardiniidae, and considered that it differs from *Cardinia* in its rounder less elongated outline, coarse regular concentric sculpture and gerontically in-grown escutcheon and nymph which have been carried down completely across the cardinal area, presumably by the descent of ligament. The outline of the species is, in fact, fairly unique but other characters are also seen to a certain extent in many species of *Cardinia*, and I am inclined to regard it as a subgenus of *Cardinia*. Besides the above mentioned groups, TORNQUIST (1898) proposed *Cardiniopsis* for a *Cardinia*-like Bajocian species from Argentina. Although the generic name was preoccupied by *Cardiniopsis* STANTON (1895) by three years, it may be related to *Cardinia* (especially to *Concinna*-group), judging from its exterior. *Cardinia gleimi* SMITH (1927) and *Cardinia ponderosa* GABB (1869) respectively from the Carnic and Noric of North America do not belong to any of my five groups. The two species are interesting ones for the consideration of the phylogeny of *Cardinia* but their generic references were doubted respectively by KOBAYASHI and ICHIKAWA (1952a) and SMITH (1927).

Among the above mentioned groups of *Cardinia*, *Unioides*- and *Piriformis*-groups are composed comparatively of a few species, and considered two specialized small branches from certain main trunks of the genus in Europe. Judging from the geological occurrences, *Toriyamai*-subgroup flourished already in the Carnic of Eastern Asia and Arctic regions prior to many other European

groups. In Europe *Concinna*- and *Crassissima*-groups and *Hybrida*-subgroup appeared almost coevally at first in the Rhaetic, and it is difficult to say which group is the oldest and forms the main stock. These three groups are very different in outline from one another, but *Hybrida*-subgroup and *Crassissima*-group may be related in many other characters. *Hybrida*-subgroup is morphologically related to *Toriyamai*-subgroup and may be a derivative from the latter. The differentiation among the two groups and the subgroups occurred anyhow already in the lower Liassic. The former subgroup flourished chiefly in Europe, while the latter prospered mainly in the Circum-Pacific and Arctic regions. *Densestriata*-subgroup is probably also a specialized branch from a certain subgroup of *Hybrida*-group, and very characteristic in the middle and upper Lias of South America (Neuquen, Patagonia and Chile). In outline the subgroup is very similar to *Toriyamai*-subgroup. Text-fig. 1 shows the possible phylogeny of *Cardinia*.

The origin of *Cardinia* has not yet been clarified. As mentioned above, some Upper Palaeozoic "*Cardinias*" could not be ancestral to the Mesozoic species. According to Diener (1923) and Kutassy (1931), no Lower or Middle Triassic species was reported, and the ancestor of this genus should be sought in other pelecypod genera of the age. Waagen (1907) discussed the phylogeny



Text-fig. 1. Evolution of *Cardinia*. Abbreviations:—T: *Torastarte*, Hd: *Densestriata*-subgroup, Ht: *Toriyamai*-subgroup, Hh: *Hybrida*-subgroup, Cr: *Crassissima*-group, Co: *Concinna*-group (*Cardinia* s. s.), Cp: *Cardiniopsis*, P: *Piriformis*-group, U: *Unioides*-group.

of *Cardinia* and concluded that the genus is a descendent group from *Trigonodus* SANDBERGER (1864). He regarded that the cardiniid hinge was introduced by the shifting of ligament from external to internal. But I think that *Cardinia* is quite different from *Trigonodus* and its related genera (i.e. *Pachycardia*, *Heminajas*, etc.) in dentition, ligament structure and external aspects which are fundamental for the classification of pelecypods. NAKAZAWA (1956) and I (1957) included *Cardinioides* KOBAYASHI and ICHIKAWA (1952a) in the Cardiniidae ZITTEL laying special weight on the presence of remote lateral teeth of *Cardinia*-type. The musculature of *Cardinioides* is also fairly similar to *Cardinia*, but the two genera differ from each other in some other fundamental characters, as shown below.

Characters	*Cardinia*	*Cardinioides*	*Trigonodus*
Outline	ovate or cuneiform	ovate or trigonal	trigonal
Umbonal direction	prosogyrous, often projected anteriorly	orthogyrous	slightly prosogyrous
Ligament	subinternal	external	external
Cardinal teeth	obsolete 3a only	pseudocardinal teeth	*Myophoria*-like teeth
Ant. lateral teeth	strong, short	absent	absent
Pos. lateral teeth	strong, remote	rounded, if present	thin, elongated
Pos.-dorsal carina	absent	absent or weak	present
Ventral sinuation	sometimes present	absent	absent
Lunule	deeply excavated	absent	absent or weak
Escutcheon	nearly vertical	absent	absent

Therefore, I am now inclined to consider that *Trigonodus*, *Pachycardia*, *Heminajas* and *Cardinioides* should be excluded from the Cardiniidae and included in a certain schizodont family. *Palaeopharus* (*Minepharus*) *triadicus* TOKUYAMA* (MS) from the Carnic of West Japan shows *Pleurophorus*-like posterior radial ornamentation and elongated outline, and at the same time *Cardinia*-like dentition composed of obsolete cardinal and incipient anterior lateral teeth, similar musculature and ligament structure. The excavated lunule in *Cardinia* is very similar to that of the Carnic species as well as other Japanese Carnic palaeopharids**. The crenulated pseudocardinal teeth in *Palaeopharus* correspond as a whole probably to the anterior lateral teeth of *Cardinia*. Although the phylogenetical relationship between *Palaeopharus* and "*Pleurophorus*" has not yet been clarified, it is possible that *Cardinia* was originated in such primitive heterodont groups with more or less elongated shells. In comparison with primitive heterodonts which were lately discussed by NEWELL (1957), *Cardinia* differs from "*Pleurophorus*" and its related genera in having a distinct anterior lateral teeth and subinternal ligament. In many respects, direct descendants

* I could observe its well-preserved specimens through his courtsey.

** NAKAZAWA (1955) regarded the pre-umbonal excavation in *Palaeopharus maizurensis* KOBAYASHI and ICHIKAWA as an anterior ligament area.

from the pleurophorids are found in *Myoconcha* SOWERBY (1824) and *Kalentera* MARWICK (1953) in the Jurassic. But it is certain that *Cardinia* is more phylogenetically related to such primitive heterodonts than *Trigonodus* and other Triassic Schizodont genera. It is notworthy that the musculature, lunule and escutcheon of *Cardinia* are fairly similar to those of the Astartidae, typical Diagenodonta, especially to *Coelastarte* BOEHM (1893) as discussed before (HAYAMI, 1958), although the dentition of *Cardinia* is quite different from astartids.

Another problem adhering to *Cardinia* is the phylogeny of unionids. POHLIG (1880–1881) noted that Carboniferous *Anthracosia*, Triassic *Uniona* and Jurassic *Cardinia* form a transitional series from najadids to cyprinids, and that *Uniona* and *Cardinia* are at the same time ancestral to recent *Unio*. The internal characters of *Cardinia* (especially European thick forms as Pl. XI, Fig. 13b) remind at a glance one of the similarity to the Unionidae. But *Cardinia* differs from any unionid genera in having the subinternal ligament, distinct lunule and escutcheon which appear in advanced forms of pelecypods. Such a regressive evolution cannot be considered. Although the Unionidae may have polyphyletic origins, cardiniids are most certainly not ancestral to any group of unionids.

Systematic Description

Family **Cardiniidae** ZITTEL

Genus *Cardinia* AGASSIZ, 1841

=*Sinemuria* DE CHRISTOL, 1841; *Pachyodon* STUTCHBURY, 1842;
Thalassites QUENSTEDT, 1856

Type species:—*Unio concinnus* SOWERBY, 1821, lower Lias and Rhaetic, England, Paris basin, Greenland and Northern Siberia. (Opinion 292)

The decision of the International Commission on Zoological Nomenclature relating to the generic name *Cardinia* was published as Opinion 292 which was rendered as the result of Cox's application (1951) entitled "Validation, under the Plenary Powers, of the generic name *Cardinia* as from AGASSIZ (1841), for use in its accustomed sense". Therefore, *Sinemuria*, *Pachyodon* and *Thalassites* are regarded as its synonyms.

Cardinia toriyamai HAYAMI, new species

Plate XI, Figures 1–11.

1938, *Cardinia* sp. listed by TORIYAMA, *Jour. Geol. Soc. Japan, Vol. 45, No. 533,* p. 251.
1958, *Cardinia* n. sp. listed by HAYAMI, *Japan, Jour. Geol. Geogr., Vol. 29, Nos. 1–3,* p. 107.

Description:—Shell medium to small for genus, equivalve, inequilateral, ovate to cuneiform in outline, expanded postero-ventrally, not strongly inflated, about 1.6 times as long as high; test very thick; antero-dorsal margin deeply excavated below umbo; postero-dorsal one gently arcuate, passing gradually into venter; both margins form as apical angle of about 50 degrees at beak, although it is not observable in external view; ventral margin slightly sinuated mesially in early stage but the sinuation gradually diminishes later; umbo very prosogyrous, protruded forwards, lying at about two-sevenths of shell-length from front; surface marked with strongly imbricated concentric lamellae, whose intervals are fairly regular but more or less narrow in early and full-grown stages; growth-lines very weak, frequently indiscernible; lunule small but ex-

tremely deep (generally impressed on internal mould), overlain by anteriorly protruded umbo, larger in left valve than in right due to a thickening of pre-umbonal margin in left valve, circumscribed and clearly defined by a sharp ridge in each valve; escutcheon subvertical, marked with oblique growth-lamellae; ligament subinternal, sunk deeply. Right valve provided with an obsolete cardinal 3b and a pair of laterals of *Cardinia*-type (AIII and PIII); 3b fairly stout, prosocline and linearly elongated in early stage, but almost degenerated later; AI and PI undeveloped, represented by slight marginal thickenings respectively; AIII elongated, gradually strengthened anteriorly; PIII short, weak, isolated from cardinal; left valve with a shallow cardinal groove (3b′) and a pair of stout isolated laterals (AII and PII); AII short but extremely strong; PII moderate in length, very strong, originated in a post-umbonal hinge-plate near the posterior end of escutcheon; all laterals abruptly interrupted at the ends by deeply sunk adductor scars; anterior scar gibbose, wedge-like, strongly impressed; posterior one orbicular and also well marked; pallial line weakly marked and most certainly entire; umbonal cavity shallow.

Measurement in mm.	Length	Height	Thickness
Holotype (MM2918) Left internal mould	44.0	29.0	6.5+
Paratype (MM2917) Right valve	44.5+	32.5	7.5+
Paratype (MM2921) Right valve	19.5	12.0	4.0

Observation and comparison:—About 20 specimens are at hand, but most of them more or less broken except for several immature individuals. The holotype (Fig. 6) and some other specimens (Figs. 1–4, 7) show typical dentition of *Cardinia*. Two paratypes (Figs. 5 and 9) and some other external moulds (Figs. 8, 10, 11) reveals splendidly imbricated concentric surface-markings. The concentrics are very widely spaced but sometimes irregular at intervals. The outline is more or less cuneiform with a slight ventral sinuation in early stage (Figs. 8, 9), but becomes more elliptical in adult. An elongated cardinal tooth 3b is seen in a juvenalium (Fig. 4), but when grown up, it is almost completely obsolete.

Cardinia was most flourished in the Liassic, especially in the Hettangian and Sinemurian of Europe, where many species have been described. Insofar as I am aware, there is no foreign species having such a magnificent imbricated surface. This species seems more related to the cardiniids hitherto known from the Upper Triassic of Japan in external features. More precisely, this is fairly similar to *Cardinia triadica* KOBAYASHI and ICHIKAWA (1952a) (NAKAZAWA, 1955) from the Carnic Nabae group in Central Japan and may be a derivative of such species. But in *triadica* the cardinal tooth 3b is more distinct and bordered by a shallow depression on each side which corresponds with a tooth-like projection of the counter valve. If considered that the cardinal was degenerated in this genus, this is a more advanced form than *triadica*. The surface of the Carnic species is marked also with more or less imbricated lamellae, but they are more irregular at intervals and obviously weaker than the present species. The length of *triadica* is 36 mm. at the largest, while it often exceeds 45 mm. in this species. *Cardinia misawensis* KOBAYASHI and ICHIKAWA (1952b) (ICHIKAWA, 1954; NAKAZAWA, 1955, 1956) from the Noric Nariwa and Carnic Nabae and Kochigatani groups are different from this in the slightly more anterior umbo and more

irregularly and densely spaced concentrics.

As to foreign species, *Cardinia regularis* TERQUEM in VORONETZ (1936) from the lower Lias near the mouth of Lena, Northern Siberia may be an ally to this, judging from the concentric lamellae, their smooth intervals and general outline. Typical *regularis* in TERQUEM (1855) from the lower Lias of Paris basin has an ovate outline and finely striated surface, and the Siberian form may be specifically different from the species. If the much larger dimensions of this species are ignored, it is not easy to find specific distinction between this and the Siberian form. But the concentric lamellae are probably still stronger in this species. The ventral sinuation, which is slightly seen in some young specimens of this species, develops in *Cardinia hybrida* (SOWERBY) (1818; STUTCHBURY, 1842; AGASSIZ, 1843; CHAPUIS and DEWALQUE, 1853; QUENSTEDT, 1856; DUMORTIER, 1867, etc.), a well known lower Liassic species from Western Europe and also in several allies which form *Hybrida*-subgroup in this paper. But the outlines of such European forms are more cuneiform with very anteriorly projected umbones, and the concentrics are much weaker, not imbricated and more densely spaced with insertions of numerous growth lamellae. In this species growth-lines are very weak and often indiscernible. *Cardinia latiplex* GOLDFUSS (1836), *C. idalia* D'ORBIGNY and *C. itea* D'ORBIGNY (BOULE, 1907) show almost smooth intervals, but their outlines are more cuneiform. *Cardinia elliptica* AGASSIZ (1843; QUENSTEDT, 1856), *C. similis* AGASSIZ (1843; TERQUEM, 1855) and *C. ovalis* (STUTCHBURY) (1842) have similar outlines to this, but their surface-ornaments are less imbricated. The ratio of length to height varies in this species to some extent. A right internal mould (Fig. 1) has a fairly elongated outline more or less similar to that of *Cardinia elongata* DUNKER (1851; DOUVILLÉ, 1921) which I include in *Concinna*-group. But it is certainly due to variation within this species, because wide-spaced concentric foldings are weakly impressed in the internal surface.

Occurrence:—Common in a fossiliferous lenticular sandstone bed belonging to the basal part of the lower Liassic Higashinagano formation at a small valley southeast of Higashinagano, Toyoda town, Toyora County in Yamaguchi Prefecture. The locality corresponds with Loc. 97 of Nbs by MATSUMOTO and ONO (1947). TORIYAMA (1938) listed *Cardinia* from this horizon at a valley of Higashinakayama, and his juvenile specimen (Fig. 4) is here identified with this species.

List of *Cardinia**

Abbreviations:—Co: *Concinna*-group (*Cardinia* s.s.), Cr: *Crassissima*-group, P: *Piriformis*-group, Hh: *Hybrida*-subgroup, Ht: *Toriyamai*-subgroup, Hd: *Densestriata*-subgroup, U: *Unioides*-group.

Unio abductus PHILLIPS, 1836, low.-up. Lias, Europe, (Hh); STUTCHBURY (1842).

Cardinia acuminata MARTIN, 1859, low. Lias, Europe, (Cr); JOLY (1936).

Cardinia amygdala AGASSIZ, 1843, low. Lias, Europe, (Hh); TERQUEM and PIETTE (1868).

Cardinia andium GIEBEL, 1861, mid.-up. Lias, South America, (Hd); PHILIPPI (1899), BURCKHARDT (1901), JAWORSKI (1915), JAWORSKI (1926), FERUGLIO (1934), WAHNISH (1924), LEANZA (1942).

* It is beyond my ability to make a complete synonymic list among many forms only from descriptions and figures. This list is, of course, synoptic one showing homonymic relations among hitherto reported species which I could refer to for this study.

Cardinia angustata AGASSIZ, 1843, low. Lias, Europe, (Co?); TERQUEM (1855).
Cardinia angustiplexa CHAPUIS and DEWALQUE, 1853, low. Lias, Europe, (Hh); TERQUEM and PIETTE (1868), JOLY (1936).
Cytherea aptychus MÜNSTER, low. Lias, Europe, (Hh); GOLDFUSS (1836).
Cardinia? aritiensis STUCKENBERG, 1898, Artinskian, Russia, (not *Cardinia*).
Pachyodon attenuatus STUTCHBURY, 1842, low.-mid. Lias, Europe; JOLY (1936).
Cardinia authelini JOLY, 1908, low. Lias, Europe.
Torastarte bensoni MARWICK, 1953, Rhaetic, New Zealand, (subgenus of *Cardinia*); FLEMING (1957).
Cardinia breoni MARTIN, 1859, low. Lias, Europe, (Cr).
Cardinia brevis MARTIN, 1859, low. Lias, Europe, (Cr).
Cardinia chillyensis TERQUEM and PIETTE, 1868, low. Lias, Europe, (P).
Cardinia collenoti MARTIN, 1859, low. Lias, Europe, (Cr).
Unio concinnus SOWERBY, 1819, Noric (?), Rhaetic-low. Lias, Europe, Northern Siberia and Greenland, (Co); ZIETEN (1830), GOLDFUSS (1836), AGASSIZ (1843), CHAPUIS and DEWALQUE (1853), TERQUEM (1855), QUENSTEDT (1856), CHAPUIS (1861), DUMORTIER (1867), TERQUEM and PIETTE (1868), POHLIG (1880–1881), VAUGHAN (1904), ROSENKRANTZ (1934), JOLY (1936), KIPARISOVA (1937).
Cardinia conjugensis WAAGEN, 1881, low. *Productus* Limestone of India, (not *Cardinia*?).
Cardinia contracta MARTIN, 1859, low. Lias, Europe, (Cr).
Cardinia copides RYCKHOLT, 1850, low. Lias, Europe, (Co); CHAPUIS and DEWALQUE (1853), TERQUEM (1855), DUMORTIER (1867), TERQUEM and PIETTE (1868).
Cardinia cordata SWALLOW, 1858, low. Permian, North America, (not *Cardinia*).
Unio crassissimus SOWERBY, 1817, low. Lias,-low. Dogger, Europe, South America (?) and Indochina (?), (Cr); STUTCHBURY (1842), QUENSTEDT (1856), TERQUEM and PIETTE (1868), DUMORTIER (1869), MANSUY (1919), DACQUÉ (1933–1934), FERUGLIO (1934), JOLY (1936).
Unio crassiusculus SOWERBY, 1817, low. Lias, Europe, (Cr), STUTCHBURY (1842), DUMORTIER (1867), TERQUEM and PIETTE (1868).
Pachyodon cuneatus STUTCHBURY, 1842, low. Lias, Europe, (Hh).
Cardinia cyprina AGASSIZ, 1843, low. Lias, Europe, (U).
Cardinia densestriata JAWORSKI, 1915, mid.-up. Lias, South America, (Hd); WEAVER (1931), LEANZA (1942).
Unio depressus ZIETEN, 1830, low. Lias, Europe, (Hh); QUENSTEDT (1856); DACQUÉ (1933–1934).
Cardinia deshayesi TERQUEM, 1855, low. Lias, Europe and South America (?), (Cr), TERQUEM and PIETTE (1868), MÖRICKE (1894).
Cardinia desoudini TERQUEM, 1855, low. Lias, Europe (Cr).
Cardinia dormali JOLY, 1908, low. Lias, Europe; JOLY (1936).
Cardinia dunkeri CHAPUIS and DEWALQUE, 1853, low. Lias, Europe, (Hh); KOCH and DUNKER (1837, *Unio trigonus*), JOLY (1936).
Cardinia elliptica AGASSIZ, 1843, low. Lias, Europe, (Ht); QUENSTEDT (1856).
Cardinia elongata DUNKER, 1851, low. Lias, Europe, (Co); TERQUEM and PIETTE (1868), PHILIPPI (1897), DOUVILLÉ (1921).
Cardinia eveni TERQUEM, 1855, low. Lias, Europe, (Co?); DUMORTIER (1864), JOLY (1936).
Cardinia exigua TERQUEM, 1855, low. Lias, Europe; DUMORTIER (1864), TERQUEM and PIETTE (1868), JOLY (1936).
Cardinia? exilis McCOY, 1847, Permian, Australia, (not *Cardinia*).

Pholadomya expansa LUNDGREN, 1878, low. Lias, Europe, (*Cardinia*?); LUNDGREN (1881), TROEDSSON (1951).

Cardinia fischeri TERQUEM, 1855, low. Lias, Europe, (Co?); TERQUEM and PIETTE (1868).

Cardinia follini LUNDGREN, 1878, low. Lias, Europe; LUNDGREN (1881), TROEDSSON (1951).

Cardinia gibba CHAPUIS and DEWALQUE, 1853, low. Lias, Europe, (Hh); TERQUEM and PIETTE (1868).

Cardinia gibbosula D'ORBIGNY, 1850, low. Lias, Europe, (Hh); BOULE (1906).

Cardinia gibbosum HYATT, 1894, up. Lias, North America.

Thalassites giganteus QUENSTEDT, 1858, low. Lias, Europe, (Co), TERQUEM and PIETTE (1868).

Cardinia gleimi SMITH, 1927, Carnic, North America, (*Cardinia*?).

Cardinia gottingensis PLÜCKER, 1868, Rhaetic, Europe, OOSTER (1869).

Cardinia hennocquii TERQUEM, 1855, low. Lias, Europe, (Co), DUMORTIER (1864), TERQUEM and PIETTE (1868).

Unio hybridus SOWERBY, 1817, low.-mid. Lias, Europe, Greenland and Northern Siberia (?), (Hh); STUTCHBURY (1842), AGASSIZ (1843), CHAPUIS (1869), DEWALQUE (1853), QUENSTEDT (1856), DUMORTIER (1867), DUMORTIER (1869), WAAGEN (1907), ROSENKRANTZ (1934), JOLY (1936), VORONETZ (1936).

Cardinia idalia D'ORBIGNY, 1850, low. Lias, Europe, (Hh); BOULE (1906).

Pachyodon imbricatus STUTCHBURY, 1842, low. Lias, Europe, (Hh); JOLY (1936).

Cardinia inexpectans WARREN, 1932, low.? Dogger, Canada.

Cardinia infera AGASSIZ, 1843, low. Lias, Europe, (Co); TERQUEM and PIETTE (1868).

Cardinia ingelensis TROEDSSON, 1951, low. Lias, Europe.

Cardinia insignis MARTIN, 1859, low. Lias, Europe, (Cr).

Cardinia itea D'ORBIGNY, 1850, low. Lias, Europe, (Hh); BOULE (1906).

Cardiniopsis jurensis TORNQUIST, 1898, low. Dogger, South America, (*Cardinia*?).

Cardinia keuperiana DITTMAR, 1864, Keuper (?) and Rhaetic, Europe.

Cardinia kullensis TROEDSSON, 1951, low. Lias, Europe, (Co).

Cardinia laevis AGASSIZ, 1843, low. Lias, Europe.

Cytherea lamellosa GOLDFUSS, 1836, low. Lias, Europe, (Hh); CHAPUIS and DEWALQUE (1853), TERQUEM and PIETTE (1868), JOLY (1936).

Pachyodon lanceolatus STUTCHBURY, 1842, low. Lias, Europe, (Co?); AGASSIZ (1843).

Cytherea latiplex MÜNSTER, low. Lias, Europe, (Hh); GOLDFUSS (1836), QUENSTEDT (1856).

Cardinia latitruncata MANSUY, 1919, mid.? Lias, Indochina.

Cardinia lerichei JOLY, 1908, low. Lias, Europe; JOLY (1936).

Unio listeri SOWERBY, 1817, Rhaetic-low. Lias, Europe, and Northern Siberia, (Hh); GOLDFUSS (1836), STUTCHBURY (1842), CHAPUIS and DEWALQUE (1853), DUMORTIER (1864), DUMORTIER (1867), TERQUEM and PIETTE (1868), OOSTER (1869), POHLIG (1880–1881), WINKLER (1886), WAAGEN (1907), JOLY (1936), VORONETZ (1936).

Cardinia lucinaeformis COSSMANN, 1904, low. Lias, Europe.

Cardinia lycetti CHAPUIS, 1858, low. Lias, Europe.

Cardinia mactroides LEVALLOIS, 1864, Rhaetic-low. Lias, Europe.

Cardinia minor AGASSIZ, 1843, low. Lias. Europe, (Cr), TERQUEM and PIETTE (1868).

Cardinia misawensis KOBAYASHI and ICHIKAWA, 1952b, Carnic, Noric (?), Japan, (Ht); ICHIKAWA, (1954), NAKAZAWA (1955), NAKAZAWA (1956).

Cardinia moreana MARTIN, 1859, low. Lias, Europe, (Cr).
Cardinia morisi TERQUEM, 1855, low. Lias, Europe, (Hh).
Cardinia nachamensis MANSUY, 1919, mid.? Lias, Indochina.
Unio nilssoni KOCH and DUNKER, 1837, low. Lias, Europe, (Hh); CHAPUIS and DEWALQUE (1853), JOLY (1936).
Cardinia oblonga AGASSIZ, 1843, Lias-mid. Dogger, Europe.
Cardinia obovata MARTIN, 1859, low. Lias, Europe, (Cr).
Cardinia oppeli CHAPUIS, 1858, low. Lias, Europe; JOLY (1908), JOLY (1936).
Pachyodon ovalis STUTCHBURY, 1842, low. Lias, Europe, (Ht); CHAPUIS (1858), JOLY (1936).
Cardinia ovula KITTL, 1907, Carnic?, Bayfjord and Northern Siberia, (Ht?), VORONETZ (1936).
Cardinia ovula KITTL, var. *polaris* VORONETZ, 1936, Carnic?, Northern Siberia; (Ht?).
Cardinia ovum MARTIN, 1859, low, Lias, Europe, (Cr?); COSSMANN (1904).
Cardinia philea D'ORBIGNY, 1850, low.-mid. Lias, Europe, Caucasus (?) and Indochina (?), (Co), DUMORTIER (1869), DUMORTIER (1869), BOULE (1906), MANSUY (1914), PČELINICEV (1937).
Cardinia piriformis TERQUEM and PIETTE, 1868, low. Lias, Europe, (P).
Cardinia plana AGASSIZ, 1843, low. Lias, Europe and Indochina (?), (P); TERQUEM and PIETTE (1868), MANSUY (1919), JOLY (1936).
Cardinia? plana STUCKENBERG, 1898, non AGASSIZ, 1843, Artinskian, Russia, (not *Cardinia*).
Cardinia ponderosa GABB, 1869, North America, (*Cardinia*?); SMITH (1927).
Cardinia porrecta CHAPUIS and DEWALQUE, 1853, low. Lias, Europe, (Co?), TERQUEM and PIETTE (1868), JOLY (1936).
Cardinia quadrangularis MARTIN, 1859, low. Lias, Europe, (Cr).
Cardinia quadrata AGASSIZ, 1843, low. Lias, Europe, (Hh); CHAPUIS (1858), JOLY (1936).
Cardinia regularis TERQUEM, 1855, low. Lias, Europe, (Cr); TERQUEM and PIETTE (1868), JOLY (1908).
Cardinia regularis VORONETZ, 1936, non TERQUEM 1855, low. Lias, Siberia, (Ht).
Cardinia scapha TERQUEM, 1855, low. Lias, Europe, (Co), TERQUEM and PIETTE (1868).
Cardinia securiformis AGASSIZ, 1843, low. Lias, Europe, (Co?), TERQUEM and PIETTE (1868).
Cardinia siberica VORONETZ, 1936, low. Lias, Siberia, (Cr).
Cardinia similis AGASSIZ, 1843, low. Lias, Europe, (Ht); TERQUEM (1855), TERQUEM and PIETTE (1868).
Cardinia sinemuriensis D'ORBIGNY, 1850, low. Lias, Europe, (Cr); BOULE (1906).
Cardinia subaequilateralis CHAPUIS and DEWALQUE, 1853, low. Lias, Europe; (U); JOLY (1936).
Cardinia? subangulata SWALLOW, 1858, Permian, North America, (not *Cardinia*).
Cardinia sublamellosa D'ORBIGNY, 1850, low. Lias, Europe, (Cr).
Cardinia subovalis MARTIN, 1859, low. Lias, Europe, (Cr); JOLY (1936).
Cardinia subtrapezoides VORONETZ, 1936, low. Lias, Northern Siberia.
Cardinia sulcata AGASSIZ, 1843, low. Lias, Europe, (Hh); DUMORTIER (1867).
Cardinia tas-aryensis VORONETZ, 1936, low. Lias, Northern Siberia, (Cr?).
Cardinia toriyamai HAYAMI, 1958, low. Lias, Japan, (Ht).
Cardinia trapezium MARTIN, 1859, low. Lias, Europe (Cr).

Cardinia triadica KOBAYASHI and ICHIKAWA (1952a), Carnic, Japan, (Ht), NAKAZAWA (1955).

Cardinia trigona DUNKER, 1851, low. Lias, Europe, (U ?); MARTIN (1859), PHILIPPI (1897).

Cardinia unioides AGASSIZ, 1843, low. Lias, Europe, (U); CHAPUIS and DEWALQUE (1853), TERQUEM and PIETTE (1868), JOLY (1936).

Cardinia wyomingensis LOGAN, 1900, Jurassic, North America.

Cardinia zeilleri JOLY, 1908, low. Lias, Europe; JOLY (1936).

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Postscript

After the manuscript of this paper had been completed, Dr. L. D. KIPARISOVA sent me a copy of her paper entitled "New Lower Jurassic Fauna near Amur. *Trans. All Soviet Union Sci. Geol. Inst.*, 1952". It comprises *Cardinia amurensis* KIPARISOVA, *C. nostra* KIPARISOVA, *C.* aff. *subacuminata* TCHERNYSHEW, *C.* aff. *collenoti* MARTIN, *C.* aff. *hennocquii* TERQUEM and *C.* ex gr. *concinna* (SOWERBY). Thus some of them were compared with European species from the lower Lias. But so far as I can judge from the illustrations, most of them appear to belong to the *toriyamai*-subgroup in my classification which is characterized by the more or less widely spaced concentric imbrications on the surface. *Toriyamai* actually resembles the Amur forms in outline, but specifically different in the stronger surface-ornamentation. (August 28, 1958)

I. HAYAMI

Taxonomic Notes on *Cardinia* with Description of a New Species from the Lias of Western Japan

Plate XI

Explanation of Plate XI

Figs. 1–11. *Cardinia toriyamai* HAYAMI, new species p.121

Fig. 1. Right internal mould (MM2913) × 1.

Fig. 2. Left internal mould (MM2914) × 1.

Fig. 3. Gypsum cast of right internal mould (MM2915) × 1.

Fig. 4. Juvenile right internal mould (MM2916) × 2. (TORIYAMA coll.)

Fig. 5. Gypsum cast of right external mould (MM2917) × 1. Paratype.

Fig. 6. Gypsum cast of left internal mould (MM2918) × 1. Holotype.

Fig. 7. Gypsum cast of right internal mould (MM2919) × 1.

Fig. 8. Gypsum cast of right external mould (MM2920) × 3/2.

Fig. 9. Gypsum cast of right external mould (MM2921) × 3/2. Paratype.

Fig. 10. Gypsum cast of right external mould (MM2922) × 1.

Fig. 11. Gypsum cast of right external mould (MM2923) × 1.

Figs. 12–18. Foreign species of *Cardinia*.

Figs. 12a–b. *Cardinia copides* RYCKHOLT × 2/3, after TERQUEM (1855, pl. 19, figs. 10, 10a).

Figs. 13a–b. *Cardinia crassissima* (SOWERBY) × 1/2, after TERQUEM and PIETTE (1868, pl. 10, figs. 3, 4).

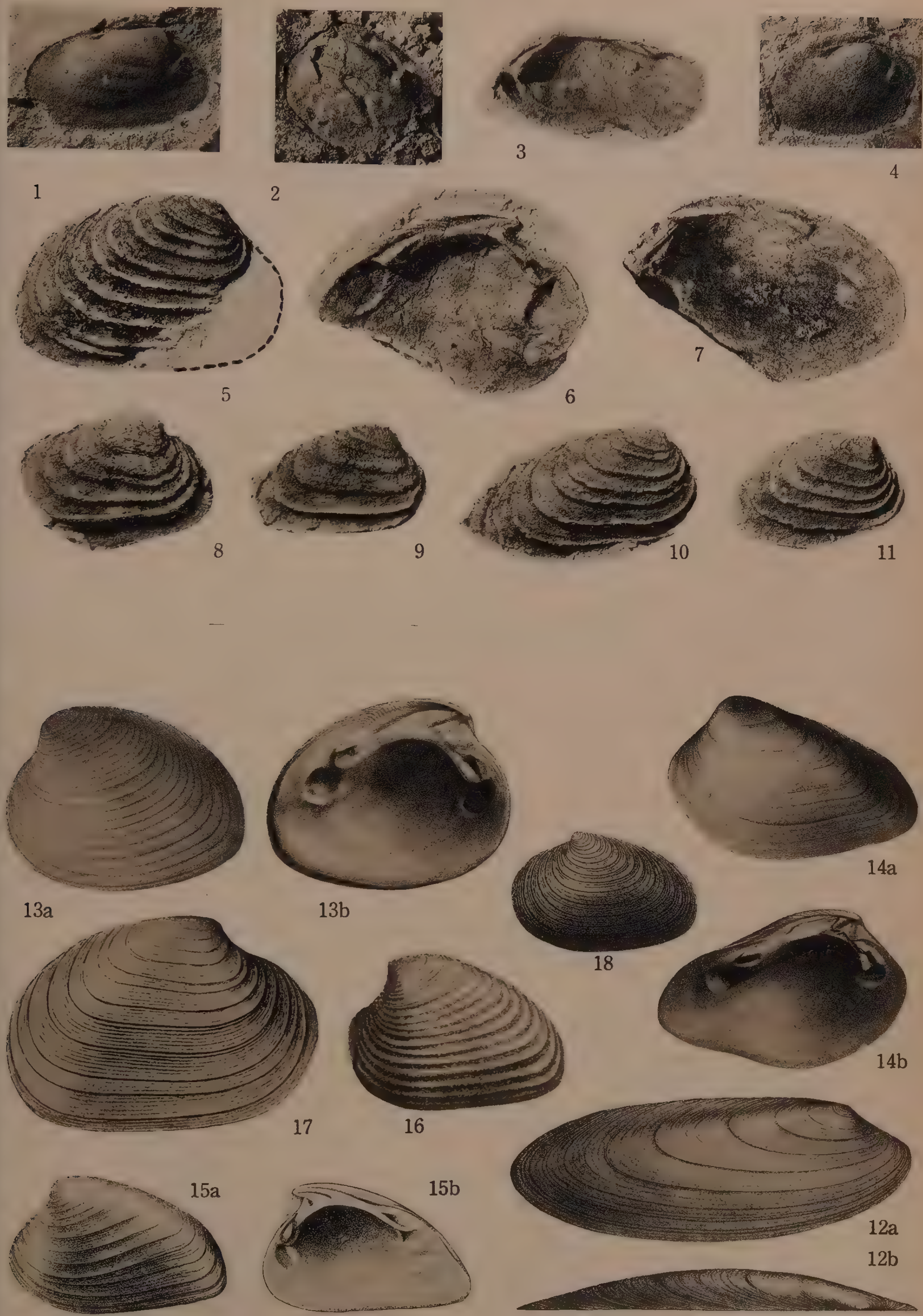
Figs. 14a–b. *Cardinia piriformis* TERQUEM and PIETTE × 4/9, after TERQUEM and PIETTE (1868, pl. 8, figs. 1, 2).

Figs. 15a–b. *Cardinia hybrida* (SOWERBY) × 2/3, after AGASSIZ (1843, pl. 12′, figs. 10, 12).

Fig. 16. *Cardinia latiplex* (MÜNSTER) × 2/3, after GOLDFUSS (1836, pl. 141, fig. 6a).

Fig. 17. *Cardinia densestriata* JAWORSKI × 1/2, after JAWORSKI (1915, pl. 5, fig. 6a).

Fig. 18. *Cardinia unioides* AGASSIZ × 2/3, after AGASSIZ (1843, pl. 12″, fig. 7).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PLUTONIC AND METAMORPHIC ROCKS OF THE NAKOSO AND IRITŌNO DISTRICTS IN THE CENTRAL ABUKUMA PLATEAU

By

Fumiko SHIDÔ

Contents

ABSTRACT

Plutonic rocks of the central Abukuma Plateau have been divided into two groups, older and younger. The intrusion of the former was roughly synchronous with regional metamorphism (late Paleozoic or early Mesozoic ?), whereas that of the latter was far later (late Mesozoic ?) and was accompanied by contact metamorphism.

In the western part of the *Nakoso district* is exposed the Tabito igneous complex belonging to the older group of intrusives, whereas in the eastern part is exposed a group of regional metamorphic rocks related. The Tabito igneous complex consists of hypersthene-augite-hornblende-gabbros, hornblende-gabbros, biotite-hornblende-diorites and hornblende-biotite-granodiorites. Probably, the basic members of the complex were emplaced and crystallized at higher temperatures than the acidic ones. The crystallization temperatures of diorites and granodiorites appear to have been lower than the values so far generally assumed.

Metamorphic rocks of the Nakoso district are composed mainly of basic rocks, with subordinate amounts of pelitic, psammitic and calcic rocks. The metamorphic area is divided into four zones representing progressive metamorphism in response to rising temperature, as follows:

Zone A, characterized by actinolite in basic rocks. The commonest type of basic rocks is epidote-chlorite-actinolite-schist.

Zone B, characterized by blue-green hornblende. The commonest types of basic rocks are epidote-blue-green hornblende-schist and blue-green hornblende-schist.

Zone C, distinguished from zone B by the presence of brown hornblende and from zone D by the absence of orthopyroxene. The commonest types of basic rocks are brown hornblende-schist and clinopyroxene-brown hornblende-schist.

Zone D, characterized by the presence of orthopyroxene. The commonest types of basic rocks of this zone are orthopyroxene-clinopyroxene-brown horn-

blende-schist and orthopyroxene-clinopyroxene-cummingtonite-brown hornblende-schist.

Minerals in the Nakoso metamorphic rocks are described in detail. The main results may be summarized as follows.

(1) *Plagioclase*. In basic rocks, the plagioclase is albite in most of zone A, oligoclase at the boundary to zone B, and becomes rapidly more calcic with advancing metamorphism, reaching labradorite in the middle-grade part of zone B.

(2) *Clinopyroxene*. All the clinopyroxenes of these metamorphic rocks are practically of the diopside-hedenbergite series. The composition field of the clinopyroxenes extends with advancing metamorphism toward decreasing Ca-content.

(3) *Potash felspar*. The transformation of the potash felspar from triclinic to monoclinic symmetry took place at the higher-grade part of zone B. Then, the phase orthoclase has its own stability field.

(4) *Amphiboles*. The existence of a miscibility gap between the actinolites and common hornblendes is shown. Compositions of hornblendes are expressed in terms of constituting molecules after a certain rule of calculation. By using these molecules, the compositional change of hornblendes is discussed in relation to the chemical and physical conditions of formation. The (Na+K) content of the hornblende or the total amount of sodatremolite and edenite molecules contained, increases generally with the rising temperature of formation, although it varies with the degree of silica saturation of their host rocks and with the composition of associated plagioclases.

The *Iritōno district*, which had been regionally metamorphosed in a low grade, was later subjected to the contact metamorphism caused by a younger intrusive, called the Iritōno igneous complex. The complex consists of hornblende-gabbros, biotite-hornblende-diorites, hornblende-biotite-granodiorites and almandine-biotite-granites.

The contact metamorphic aureole of the Iritōno district consists mainly of basic rocks and is divided into three progressive zones, A′, C′ and D′ based on the characters of the calciferous amphiboles similarly as in the Nakoso district. Zones A′, C′ and D′ correspond to zones A, C and D respectively. However, there are some differences in character of metamorphism between the two districts: (1) In the Iritōno district, basic rocks of zone A′ are practically devoid of epidote and have very calcic plagioclase instead. Accordingly, the characteristic assemblage of this contact-metamorphic zone A′ is actinolite-chlorite-labradorite, which does not belong to any of the mineral facies so far known. (2) Zone B′ corresponding to zone B does not exist in the Iritōno contact aureole. The transformation temperature of actinolite to common hornblende was probably higher in the Iritōno contact metamorphism than in the Nakoso regional one. It is discussed that the Iritōno contact metamorphism took place under lower rock pressures than the Nakoso regional one.

From the comparison of the (Na+K) contents of hornblendes from the various metamorphic terrains, it is concluded that the contents differ in different types of metamorphism and higher contents generally represent higher rock pressures. It is also discussed that the epidote-amphibolite facies develops more extensively in metamorphism under higher rock pressures and the formation of pyralspite and cummingtonite in amphibolite is related to types of metamorphism.

INTRODUCTION

The central Abukuma Plateau, about 150–200 km north-north-east of Tokyo, has been studied by many geologists. K. WATANABE and M. SATO (1935) published a geological map (scale 1/75,000) of the Nakoso district in it. K. SUGI (1935) gave a brief survey of the metamorphic rocks of this region. M. GORAI (1944) and I. WATANABE et al. (1955) studied the igneous rocks extensively exposed in the Plateau. A. MIYASHIRO (1953 a, b) described the progressive metamorphism of calcic rocks and clarified the compositional variation of pyralspite garnet in pelitic rocks with advancing metamorphism in the Gosaisyo-Takanuki district.

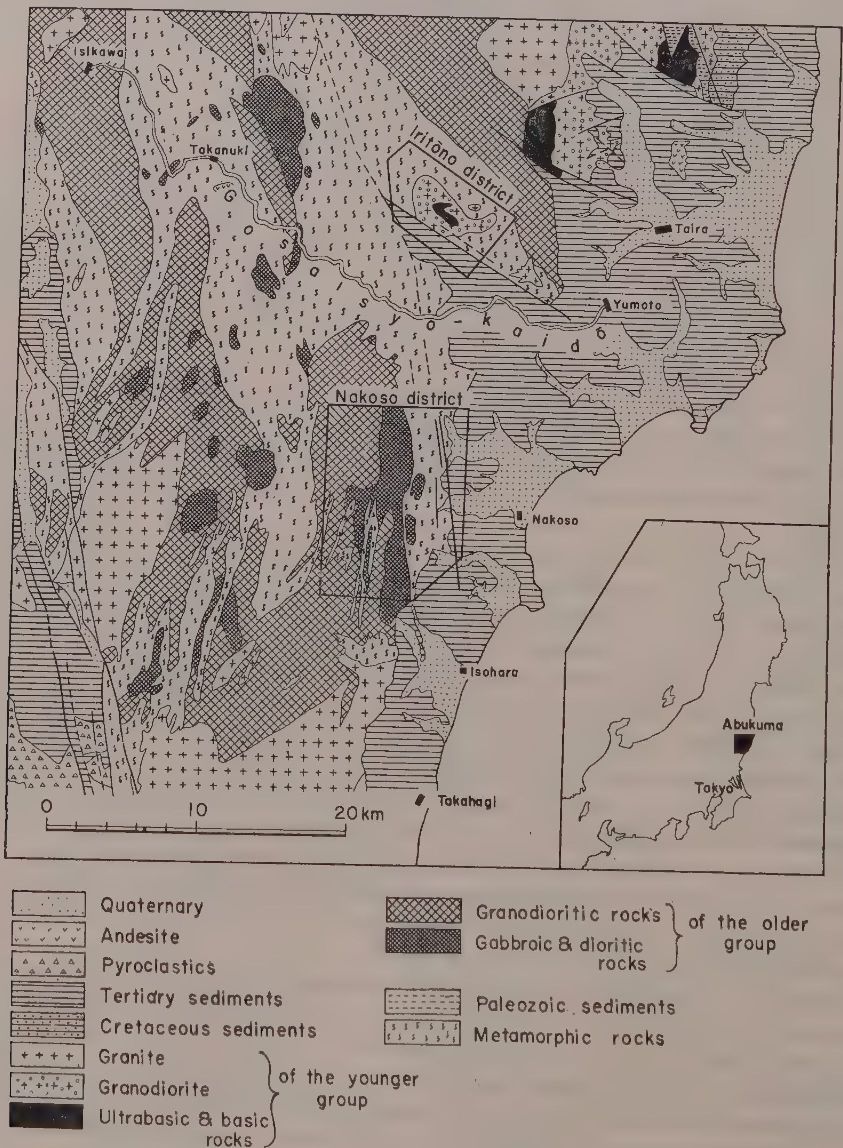

Fig. 1. Geological sketch map of the central Abukuma Plateau, compiled on the basis of geological survey by M. GORAI, I. WATANABE, and others.

Further, he (MIYASHIRO, 1958) has written comprehensive descriptions and discussions on the progressive metamorphism of the same district.

In the central Abukuma Plateau, plutonic and metamorphic rocks are extensively exposed. The plutonic rocks intruded into the metamorphic rocks to form several separate masses.

M. GORAI (1944) and I. WATANABE et al. (1955) have divided the plutonic rocks of the district into two groups: older and younger. These rocks are mainly diorites and granodiorites with subordinate amounts of gabbros and granites. The intrusion of the plutonic masses of the older group probably took place at or immediately after the culmination of the regional metamorphism and this represents the syn- or late-orogenic igneous activity in the structural development of the Abukuma Plateau. On the other hand, the intrusion of the plutonic masses of the younger group represents the post-orogenic one. I. WATANABE et al. (1955) consider that the intrusion of the older group was in late Paleozoic or early Mesozoic time, and that of the younger group was in early or middle Cretaceous time.

In general, basic metamorphic rocks are relatively abundant in the eastern half of the central Abukuma Plateau, whereas pelitic and psammitic rocks are relatively abundant in the western half. A. MIYASHIRO (1958) shows that the metamorphic grade generally increases westward on a regional scale, though the distribution of metamorphic grades is somewhat modified by the thermal effects of intrusive masses of the older group.

In this paper, I intend to give the results of my petrological and mineralogical studies of plutonic and metamorphic rocks of the Nakoso district, which is situated in the south-eastern part of the central Abukuma Plateau. Plutonic rocks of the older group and related regional metamorphic rocks are exposed in the district. I studied also plutonic and associated contact-metamorphic rocks in the Iritōno district for comparison, as the plutonic rocks of this district belong to the younger group. The results also will be given briefly. These districts are shown in Fig. 1.

PART I. THE NAKOSO DISTRICT

1. General Statement

As shown in Fig. 2, the western half of the present district is occupied by plutonic rocks and the eastern half by metamorphic rocks and Tertiary sediments. The Tertiary sediments abut upon the metamorphic rocks unconformably, except where they are in fault contact. The schistosity and bedding planes of metamorphic rocks in the present district trend nearly north-south with an approximately vertical dip. The plutonic rocks are intrusive into the metamorphic rocks along this trend, to form three masses; GORAI (1944) called two smaller masses of them (En and Es in Fig. 2) "the Kawabe gabbroic stocks" and the remainning one (W in Fig. 2) "the Tabito igneous complex". M. GORAI and I. WATANABE et al. classed the Tabito into the older group and the Kawabe into the younger. However, I could not find any justification for this age distinction from geological as well as petrological point of view. My study of the metamorphism of the district indicates that all these igneous rocks belong to the older group. Then, I will call all of them "the Tabito igneous complex".

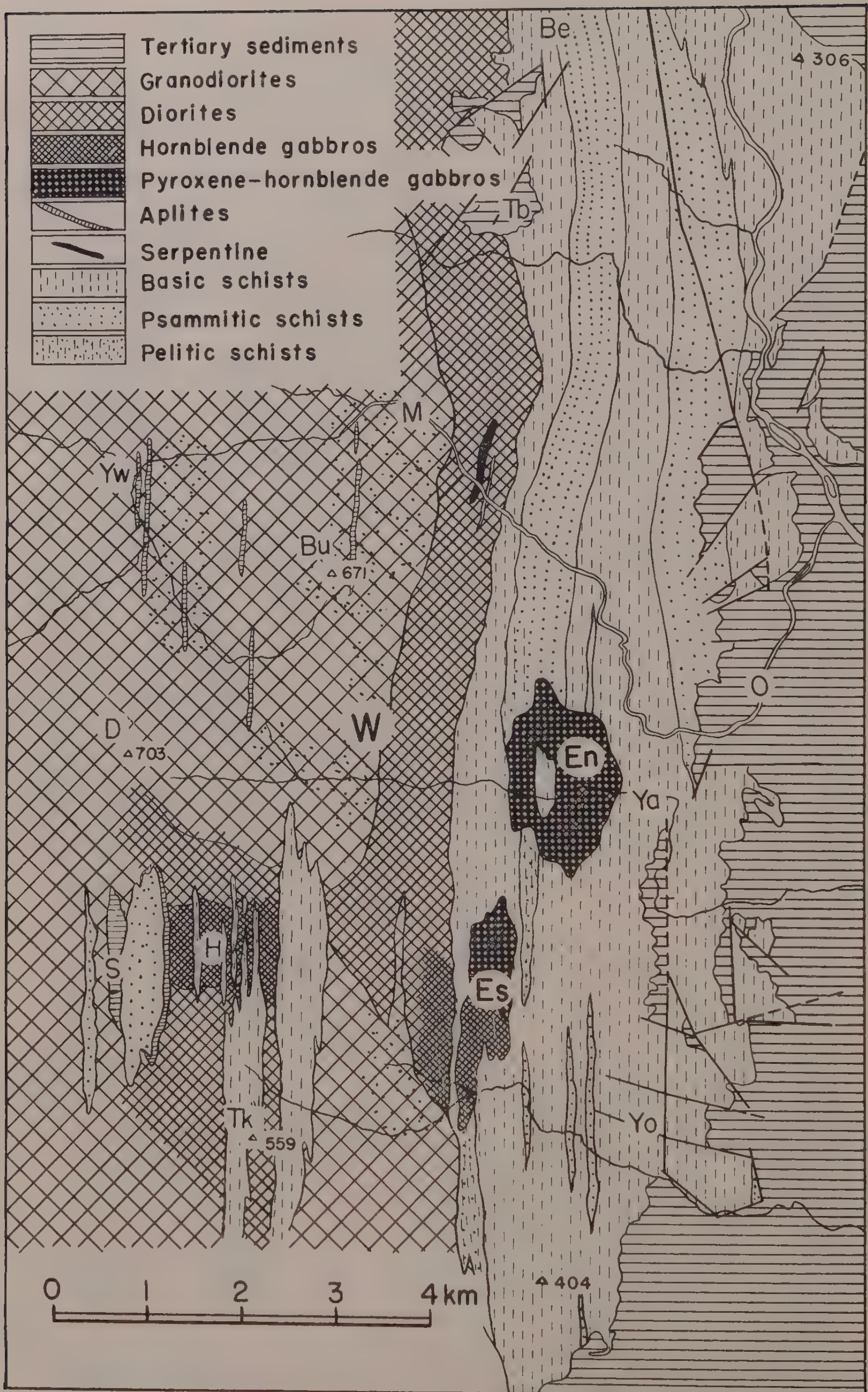

Fig. 2. Geological map of the Nakoso district. En, Es and W represent the En Es, and W masses respectively.
Be: Bettō, Bu: Butugu-yama, D: Daimaru-yama, H: Hatatate-tōge, M: Minami-ōdaira, O: Ogawa, S: Saimaru, Tb: Tabyūto, Tk: Takanosu-yama, Ya: Yamatama, Yo: Yōzikata, Yw: Yokogawa. The numerals represent the heights of mountains above sea level.

Many faults run through the metamorphic as well as the Tertiary rocks, but it appears that the regional zonal arrangement of the metamorphic grade within the district is not disturbed by them. This probably indicates that these faults, synchronous or later than the deposition of the Tertiary sediments, have large dip angles and small strike-slips.

The metamorphic area of the district is divided into four zones, A, B, C, and D, in the order of increasing grade of metamorphism as will be explained later (Fig. 7). Zone A corresponds to the actinolite-greenschist facies. Zones B and C correspond to the amphibolite facies. Zone D belongs to the lower-grade part of a facies intermediate between the granulite and pyroxene-hornfels facies.

2. Tabito Igneous Complex

Introductory Statement

The Tabito igneous complex streches southward from the present district to the Hitati, occupying an area of about 250 square km.

The Tabito igneous complex in the present district consists of three intrusive units as stated before, and *these units are denoted by En, Es and W* (Fig. 2). The rocks of the complex are varied in composition and hence are divided into six petrographic groups. They are in the order of decreasing basisity as follows:

1. Serpentine.
2. Pyroxene-hornblende-gabbros, including cortlandtite and gabbro pegmatite.
3. Hornblende-gabbros, intermediate between the above gabbro and the following diorite group.
4. Diorites.
5. Granodiorites.
6. Aplites.

It is difficult to draw a clear distinction between the pyroxene-hornblende-gabbros and hornblende-gabbros or between the hornblende-gabbros and diorites. A complete compositional gradation is observed and therefore the grouping is rather arbitrary. The characteristic features of these petrographic groups are summarized below:

Pyroxene-hornblende-gabbros: The rocks of this group are characterized by the presence of light-brown common hornblende, usually in abundance. The other chief consituents commonly observed are plagioclase, orthopyroxene, clinopyroxene and cummingtonite. Olivine and spinel are abundant in rare cases. Biotite is not uncommon, though always scarce. The plagioclase ranges from anorthite to labradorite.

Hornblende-gabbros: The rocks of this group are distinguished from the above by the presence of greenish brown hornblendes, and from the following by a smaller amount of biotite. Cummingtonite is sometimes abundant and quartz is not uncommon as an accessory constituent. The plagioclase is labradorite.

Diorites: The rocks of this group are characterized by the presence of brownish green hornblende and the greater abundance of biotite and quartz. The plagioclase is calcic andesine.

Granodiorites: The rocks of this group are characterized by the presence of emerald-green hornblenede and potash felspar and the abundance of biotite and quartz. The presence of sphene, allanite and epidote is also characteristic of this group. The plagioclase is sodic andesine.

Aplites: The chief constituents are microcline, quartz and biotite. The rocks of this group are characteristically devoid of amphibole.

The mineral compositions of the various rock types, disregarding later alterations, are shown in Table 1, where the rocks are arranged in the order of decreasing basisity. The table indicates the appearance and disappearance of the various minerals in a definite order.

Table 1. Mineral compositions of the various rock types..

Rock types	Minerals / Specimen Nos.	Olivine	Orthopyroxene	Augite	Cummingtonite	Brown hornblende	Green-brown hornblende	Green hornblende	Bluish green hornblende	Biotite	Quartz	Potash felspar	Spinel	Sphene	Allanite	Epidote	Plagioclase % An
Pyroxene-hornblende-gabbros	FS 56112837	+	−	+	+	+							−				94
	FS 56113006		+	+		−				−							92
	FS 56112838			+		+											88–86
	FS 54D1		+	−	−	+				−							82
	FS 56112909		−			+				−							72
	FS 54C3		+	+	−	+											71–61
	FS 56113007		+		+	+				−							57
	FS 56113008		−	−	−	+					−						57–49
	FS 56113010		+		+		+			−	−						75–58
	FS 56113012		+	−			+			−							57–54
Hornblende-gabbros	FS 56113005				−		+			−	−						64–37
	FS 56051204						+			−							50–44
	FS 56051201				+		+			+	−						53–49
Diorites	FS 56112833							+		+	−						50–42
	FS 56051204							+		+	−						53–48
	FS 56112834							+		+	+						50–37
	FS 56112812							+		+	+						51–33
	FS 56112835							+		+	+	−					
Granodiorites	FS 56112819								+	+	+	−		−	−	−	35–33
	FS 56112814								+	+	+	−		−	−	−	40–37
	FS 56113023									+	+	+			−		37–31
	FS 56113026								−	+	+	+			−		
Aplites intrusive into gabbros	FS 56112907									−	+	−					
	FS 56113009									−	+	+					
	FS 56051203									+	+	+					
Aplites intrusive into diorites	FS 56112836*									+	+	+					
	FS 56112814									+	+	+					
Aplites intrusive into granodiorites	FS 56112821									−	+	+					
	FS 56112829									−	+	+					
	FS 56112818									−	+	+					

Note: Plagioclase is abundant in all rocks. Apatite and opaque minerals are omitted from this table.

+: abundant.

−: less abundant.

*: with almandine.

The En Mass

The En mass consists mainly of fine- to coarse-grained gabbros. The contacts are concordant with the schistosity of the adjacent metamorphic rocks, having a vertical dip. Gneissosity is lacking. The grain-size tends to be coarser in the interior of the mass. The gabbro includes a large mass of basic metamorphic rocks in the center. Small xenoliths, although absent in the interior of the mass, are fairly abundant near the contacts with schists. Dikes of aplite and leucocratic veins intrude the marginal part of the mass. The dikes have chilled margins, about 20 cm. in width, and veins also have sharp boundaries against the adjacent gabbros. Fig. 3 represents a sketch of one of the dikes.

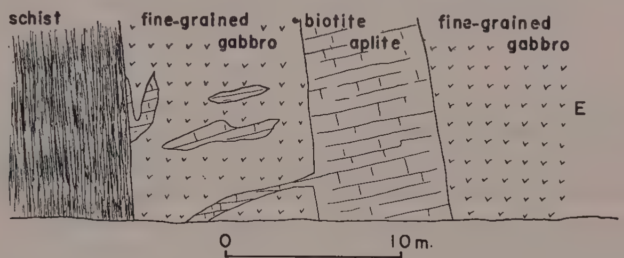

Fig. 3. Sketch of an aplite dike intrusive into the marginal facies of the gabbro mass En.

This mass is the most basic among the three. The constituting rock types are as follows: (1) cortlandtite, (2) pyroxene-hornblende-gabbros, (3) hornblende-gabbro pegmatites. Pyroxene-hornblende-gabbros are the most abundant. The distribution of these rock types within the mass appears to be irregular, except gabbro pegmatites which form pockets in the marginal part of the mass.

(1) Cortlandtite.

This rock type was found only in a boulder which was surely derived from the mass. A typical specimen from the boulder is described below.

Cortlandtite (Specimen No. FS 56112837)

Chief const.: olivine ($2V_X=80°$, $\alpha=1.696$, $\beta=1.715$; $Fo_{69}Fa_{31}$, enclosed by light-brown hornblendes), cummingtonite ($2V_Z=75°$, $Fe^{+2}/(Mg+Fe^{+2})=0.47$), hornblende (poikilitic, $2V\doteqdot 90°$, $\gamma=1.681$, X=pale yellow, Y=Z=light-brown), diopsidic augite, plagioclase (An_{94})$>>>$green spinel (hercynitic ?), magnetite, orthopyroxene.

Accessory const.: talc-like mineral (secondarily derived from olivine).

(2) Pyroxene-hornblende-gabbros.

The chief constituents are light-brown hornblende and plagioclase. Rhombic and monoclinic pyroxenes are also abundant in some specimens. Cummingtonite and biotite are constant members of this group. The grain-size is variable from fine to coarse. Poikilitic crystals of brown hornblende may reach 5 cm. in length, much larger than all other constituents. Typical specimens of this group are described below.

Augite-cummingtonite-orthopyroxene-hornblende-gabbro (Specimen No. FS 54D1; the analysis given in Table 2)

Texture: medium-grained, non-porphyritic.

Chief const.: plagioclase (An_{82}), hornblende (poikilitic, $\gamma=1.685$, $2V_X=70.5$, disp. r$>$v, X=very pale yellow, Y=Z=brown)$>$orthopyroxene (showing exsolution lamellae, $2V_X=63°$, $\gamma=1.705$, r$>$v, $En_{73}Fs_{27}$)$>$cummingtonite$>$diopsidic augite, opaque mineral, biotite

(β=1.646, Z=light-brown). (The orthopyroxene is enclosed by cummingtonite, which in turn is rimmed by common hornblende.)

Accessory const.: chlorite (probably derived from hornblende).

Augite-hornblende-gabbro (Specimen No. FS 56112838)

Texture: medium-grained, massive.

Chief const.: hornblende ($2V_X=84°$, $\gamma=1.674$, r>v, X=colorless, Y=Z=light-brown), plagioclase (An_{88-86})>diopsidic augite, tremolitic amphibole (probably derived from brown hornblende, $2V_x=76°$, r>v, X=Y=Z=colorless). (The refractive indices of the tremolitic amphibole are lower than those of the brown hornblende.)

Accessory const.: opaque mineral, apatite, chlorite (scondary).

Orthopyroxene-cummingtonite-hornblende-gabbro (Specimen No. FS 56112909)

Texture: very fine-grained, non-porphyritic.

Chief const.: plagioclase (An_{71}), hornblende ($2V_X=78°$, $\gamma=1.690$, X=light-yellow, Y=Z =light-brown)>>opaque mineral, cummingtonite>>biotite, orthopyroxene ($2V_X=56°$, disp. r>v, $En_{64}Es_{36}$).

Accessory const.: apatite.

(3) Hornblende gabbros

The chief constituents are plagioclase and brown or greenish brown hornblende. Biotite and cummingtonite are constant members of this type, though always less abundant. In general, the plagioclase is labradorite. A typical specimen of this group is described below.

Cummingtonite-hornblende-gabbro (Specimen No. FS 54D14)

Texture: medium-grained and porphyritic with hornblende phenocrysts.

Chief const.: plagioclase (three-layered zoning is observed; core=An_{86}, mantle=An_{74}, rim=An_{58}), hornblende (poikilitic, $2V_X=80°–90°$, $\gamma=1.683$, Y=colorless, Y=Z=light-brown)>>cummingtonite (sometimes included in brown hornblende and sometimes as separate individuals)>biotite (β=1.628, included within the brown hornblende).

Accessory const.: opaque mineral, chlorite (secondarily derived from hornblende).

(4) Gabbro pegmatites

These rocks were found always in the vicinity of the contacts where basic schistose xenoliths are crowded. They are similar to the above mentioned hornblende-gabbros in composition and in the characters of each constituent mineral, but differs in the greater abundance of plagioclase and the larger grain-size. The gabbro-pegmatites are sometimes accompanied by small masses of anorthosite. The anorthosites are composed essentially of plagioclase (sodic bytownite to labradorite) with a little muscovite, hornblende and chlorite, showing granular texture. The plagioclase is strongly zoned.

Aplite Dikes: At the end of this section, a brief account of the aplite dikes cutting through the En mass will be given below. The aplite may or may not be co-magmatic with the rocks of the mass.

Aplite (Specimen No. FS 56112907, obtained from the center of the aplite dike shown in Fig. 3)

Texture: medium-grained.

Chief const.: quartz>plagioclase (oligoclase)>>microcline (showing magnificent quadrille structure), biotite.

Accessory const.: apatite, tourmaline, zircon (enclosed within biotite).

The Es Mass

The Es mass consists mainly of fine- to coarse-grained pyroxene-hornblende-gabbro and hornblende-gabbro. The contacts are concordant with the schistosity of the adjacent metamorphic rocks, having a vertical dip. Gneissosity is lacking.

Leucocratic veins intrude the marginal part of the mass, and especially frequently the southern marginal part where hornblende-gabbro predominates.

This mass is a little more acidic than the En mass. The constituting rock types are: (1) pyroxene-hornblende-gabbros, (2) hornblende-gabbros and (3) gabbro-pegmatites. The rocks belonging to the first and second groups are much more abundant than those of the last. In general, basicity decreases southward. Pyroxene-hornblende-gabbros predominate in the northern part, whereas hornblende-gabbros in the southern part.

(1) Pyroxene-hornblende-gabbros

These rocks are practically identical in petrographic characters to the pyroxene-hornblende-gabbros of the En mass.

Two typical specimens of this group are described below.

Orthopyroxene-augite-hornblende-gabbro (Specimen No. FS 56113006)

Texture: fine-grained, non-porphyritic.

Chief const.: plagioclase (strongly zoned with a core of bytownite and a thin rim of andesine)>orthopyroxene (showing exsolution lamellae; $2V_X=56°$, r>v, $En_{64}Fs_{36}$), diopsidic augite ($2V_Z=53.5°$) tremolitic amphibole ($2V_X=78°$, secondarily derived from brown hornblende), hornblende (poikilitic, $2V \fallingdotseq 90°$, r<v, $\gamma=1.680$, X=colorless Y=Z=light-brown).

Accessory const.: opaque mineral.

Orthopyroxene-augite-hornblende-gabbro (Specimen No. FS 54C3; the analysis given in Table 2)

Texture: fine-grained, non-porphyritic.

Chief const.: plagioclase (showing two-layered zoning; the core=An_{71} and the margin=An_{61})>hornblende ($2V_X=78°$, X=colorless, Y=Z=brown), orthopyroxene (with exsolution lamellae; $2V_X=45°–47°$, disp. r>v, $En_{52}Fs_{48}$), diopsidic augite.

Accessory const.: opaque mineral.

(2) Hornblende-gabbros

These rocks are also practically identical in petrographical characters to the hornblende-gabbros of the En mass.

Typical specimens of this group are described below.

Biotite-bearing hornblende-gabbro (Specimen No. FS 56113005)

Texture: fine-grained, non-porphyritic.

Chief const.: plagioclase (showing two-layered zoning, with a core=An_{64} and a margin=An_{37})>hornblende ($2V_X=64°$, $\gamma=1.688$, X=yellow, Y=Z=greenish brown)>biotite>>cummingtonite, quartz.

Accessory const.: opaque mineral, apatite.

Biotite-bearing-hornblende-gabbro (Specimen No.FS 56051316)

Texture: medium-grained, non-porphyritic.

Chief const.: hornblende (enclosing numerous fine opaque plates along cleavages, $2V_X=77°$, $\gamma=1.688–1.694$, X=light-yellow, Y=Z=brown)>plagioclase (with normal zoning,* An_{60-44})>>>biotite ($\beta=1.644$).

Accessory const.: opaque mineral.

Biotite-hornblende-gabbro (Specimen No. FS 56051201)

Texture: medium-grained, non-porphyritic.

Chief const.: plagioclase (with weak normal zoning; An_{53-49})>hornblende ($2V_X=69°$, $\gamma=1.685$, X=light-yellow, Y=Z=greenish brown, sometimes enclosing cummingtonites), biotite ($\beta=1.651$, partly altered into chlorite)>tremolitic amphibole ($2V_X=75°$, fibrous, derived from brown hornblende), cummingtonite, chlorite.

Accessory const.: apatite, opaque mineral.

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* The zonal structure with increasing Ab content toward the margin is called normal zoning in this paper.

(3) Gabbro-pegmatites

These rocks are less frequently observed in this mass than those of the other types mentioned above. The modes of occurrence and petrographical characters of the rocks are similar to those of the En mass.

(4) Aplites

Many aplitic veins, a few to 30 cm. thick, intrude the hornblende gabbros. Some of the veins are practically devoid of colored minerals. A typical specimen will be described below.

Biotite-aplite (Specimen No. FS 56051203)

Texture: fine-grained.

Chief const.: quartz, microcline (showing clear quadrille twinning, $2V_X=72°$), plagioclase (oligoclase).

Accessory const.: biotite.

The W Mass

The W mass consists mainly of granodiorite, diorite, and hornblende gabbro. The contacts are concordant with the schistosity of the adjacent metamorphic rocks, having a nearly vertical dip. Gneissosity is weak or lacking in most parts, but it is fairly strong in some exposures of the western part of the mass. Dark inclusions (distinct from the amphibolite to be mentioned) show parallel arrangement in many exposures. This structure, being probably due to flow movement of the mass, is very remarkable in some places, but not recognized in others. These parallel structures have a trend concordant with the schistosity of the surrounding metamorphic rocks, having nearly NS strikes. Dark inclusions are abundant generally in the granoriorite and less abundant in the more basic rocks. The dotted fields in Fig. 2 represent the areas where dark inclusions make up a third or more of the whole rocks. The W mass includes amphibolite masses of such large sizes as can be shown on the map in the south. The amphibolite masses are elongated parallel to the schistosity. The actual contact between the granodiorite, diorite and hornblende-gabbro has not been observed. Probably all of them jointly form a single intrusive body.

This mass is intruded by many dikes and veins of granitic and aplitic rocks. The largest dike is about 100 m. or more in width. These dikes and veins can be traced for a long distance along the NS strike. Only some large dikes among them are represented on the map.

A serpentine mass occurs in the diorite. As the mass is composed of serpentine mineral, it may be regarded as having been emplaced into the already solidified diorite.

The W mass is mainly composed of the following rock types in the order of decreasing basicity: (1) pyroxene-hornblende-gabbros, (2) hornblende-gabbros, (3) diorites and (4) granodiorites. The granodiorites are much more abundant than the others and the pyroxene-hornblende-gabbros are much less abundant.

(1) Pyroxene-hornblende-gabbros.

The chief constituents are plagioclase, light-brown or brown hornblende and orthopyroxene. Augite and cummingtonite are also abundant in some specimens. The grain-size is variable from fine to medium. Porphyritic structure is usually lacking. Light-brown or brown hornblende, characteristic of this type, is often altered into pale olive-green one from its marginal part, and sometimes the whole crystal has changed to greenish brown one. The plagioclase is labradorite in most cases. Typical specimens are described below.

Orthopyroxene-cummingtonite-hornblende-gabbro (Specimen No. FS 56113010; the analysis given in Table 2)

Texture: medium-grained, non-porphyritic.

Chief const.: plagioclase (An_{58})>orthopyroxene ($2V_X=54.5°$, r>v, $En_{64}Fs_{36}$, with a very small amount of exsolution lamellae), cummingtonite ($2V_z=73°$, Cu_{53} Gr_{47}), hornblende ($2V_X=70°$, $\gamma=1.682$, r>v, X=light-brown Y=Z=greenish brown)>>biotite. (The orthopyroxene is enclosed by cummingtonite, which in turn is rimmed by common hornblende.)

Accessory const.: opaque mineral.

Augite-orthopyroxene-cummingtonite-hornblende-gabbro (Specimen No. FS 56113008)

Texture: medium-grained, non-porphyritic.

Chief const.: plagioclase (weakly zoned in normal order, An_{49-57}), hornblende (poikilitic with inclusions of plag., pyroxenes, cummingt.; $2V_X=73°$, r>v, $\gamma=1.688$, X=light-yellow, Y=Z=brown)>quartz>>augite ($\gamma\doteqdot1.719$), orthopyroxene (enclosed by brown hornblende, and showing exsolution lamellae, $\gamma=1.702$, $En_{72}Fs_{28}$), cummingtonite>biotite.

Accessory const.: opaque mineral, apatite.

Orthopyroxene-cummingtonite-hornblende-gabbro (Specimen No. FS 56113007)

Texture: fiine-grained, non-porphyritic. Lath-shaped crystals of plagioclase and of orthopyroxene show parallel arrangement to some extent.

Chief const.: plagioclase (An_{57})>orthopyroxene ($2V_X=48°–50°$, $\gamma=1.715$, r>v, $En_{58}Fs_{42}$. showing exsolution lamellae)>>hornblende ($2V_X=75°$, r>v, $\gamma=1.686$, X=colorless, Y=Z=greenish brown), cummingtonite>biotite.

Accessory const.: opaque mineral.

Augite-orthopyroxene-hornblende-gabbro (Specimen No. FS 56113012)

Texture: fine-grained, non-porpyritic.

Chief const.: plagioclase (showing weak normal zoning; An_{57-54})>orthopyroxene (with well developed exsolution lamellae, $2V_X=48°$, r>v, $En_{55}Fs_{45}$)>>>biotite, augite ($2V_Z=48°$), hornblende ($2V_X=74°$, $\gamma=1.684$, X=light-brown, Z=brownish green).

(2) Hornblende-gabbros

The chief constituents are plagioclase and light-olive hornblende. Biotite and cummingtonite are also common, though less abundant. Quartz is scanty or absent. The plagioclase is of about $Ab_{50}An_{50}$. A typical specimen is described below.

Quartz-biotite-bearing hornblende-gabbro (Specimen No. FS 56112833)

Texture: medium-grained, weakly mottled with felsic patches.

Chief const.: plagioclase (showing two-layered normal zoning with a core=An_{50} and a margin=An_{42}), hornblende ($2V_X=77.5°$, $\gamma=1.677$, r>v, X=pale yellow to nearly colorless, Y=Z=light-olive)>>biotite ($\beta=1.634$), quartz.

Accessory const.: opaque mineral, chlorite (derived from hornblende).

(3) Biotite-hornblende-diorites.

The chief constituents are plagioclase, green hornblende and biotite. Quartz is sometimes fairly abundant. Potash felspar is scanty or absent. The grain-size is medium. The compoition of the plagioclase is $Ab_{50}An_{50}$ or more sodic. The potash felspar is probably orthoclase or near it. Typical specimens are described below.

Biotite-hornblende-quartz-diorite (Specimen No. FS 56112834; the analysis given in Table 2)

Texture: fine-grained, non-porphyritic.

Chief const.: plagioclase (showing two-layered zoning with a core=An_{50} and a margin =An_{37})>hornblende ($2V_X=77.5°$, $\gamma=1.675$, X=colorless to pale green, Y=yellowish green, Z=light-green), quartz, biotite ($\gamma=1.650$, X=pale yellow, Y=Z=dark brown)

Accessory const.: apatite, opaque mineral, zircon.

Biotite-hornblende-quartz-diorite (Specimen No. FS 56112835)

Texture: medium-grained, non-porphyritic.

Chief const.: plagioclase (showing normal zoning, An_{51-33})>biotite ($\beta=1.656$), hornblende

($2V_X=65°$, $\gamma=1.688$, r>v, X=pale yellow, Y=yellowish green, Z=light-green), quartz >>>>potash felspar.

Accessory const.: apatite, opaque mineral.

(4) Granodiorites.

The chief constituents are plagioclase, biotite, hornblende and quartz. Potash felspar is present in a small amount. Always biotite predominates over hornblende. Allanite, sphene, and epidote occur characteristically though in small amount. The axial color of Z in the hornblende is emerald-green. In the potash felspars, the optic angles range from 62° to 66° and quadrille structure is lacking. Typical specimens are described below.

Biotite-hornblende-granodiorite (Specimen No. FS 56112819)

Texture: coarse-grained, mottled with light-colored clots consisting of plagioclase and/or quartz.

Chief const.: plagioclase (An_{35-33})>biotite ($\beta=1.656$, X=pale yellow, Z=dark brown)> quartz, hornblende ($2V_X=50°$, $\gamma=1.688$, r>v, X=pale yellow, Y=Z=emerald-green)> potash felspar (occurs interstitially, without quadrille twinning, $2V_X=62°$).

Accessory const.: allanite, sphene, epidote, apatite, zircon.

Hornblende-biotite-granodiorite (Specimen No. FS 56112814; the analysis given in Table 2)

Texture: coarse-grained, porphyritic.

Chief const.: plagioclase (showing weak normal zoning; An_{40-37}), quartz>biotite (X=pale yellow, Y=Z=dark brown to nearly opaque)>hornblende ($2V_X=50°$, $\gamma=1.690$, r>v, X= pale yellow, Y=yellowish green Z=emerald-green)>potash felspar (occurs interstitially without quadrille twinning, $2V_X=63°$).

Accessory const.: allanite, zircon, sphene (in contact with the hornblende), epidote (surrounding the allanite).

Biotite-granodiorite (Specimen No. FS 56113023; the analysis given in Table 2)

This rock is the most acidic among the above described granodiorites.

Texture: medium-grained.

Chief const.: plagioclase (showing weak normal zoning; An_{37-31})>quartz, microcline (with quadrille twinning, $2V_X=66°$), biotite ($\beta=1.652$, Z=light-brown).

Accesory const.: muscovite, zircon.

The Dikes and Veins:

Numerous dikes and veins intrude the W mass at places. They are composed, regardless of their country rocks, mainly of quartz, microcline and sodic plagioclase with a small amount of biotite, and sometimes have such accessory constituents as apatite, zircon, epidote, muscovite, sphene and allanite. In extremely rare cases, pyralspite garnet is associated with biotite. The plagioclase is oligoclase or more sodic. The microcline shows well-developed quadrille structure and the optic angle over X is about 78°.

The Serpentine:

The serpentine, mentioned before, is composed mainly of serpentine mineral and subordinately of magnetite, with a small amount of talc. It is utterly devoid of any mineralogical and textural relicts. The magnetite occurs as fairly large crystals scattered in the serpentine matrix. Under the microscope, serpentine is colorless, and scaly in finely crushed powder, and has $\gamma=1.559$.

Dark Inclusions:

The granodiorite is crowded with dark inclusions. The shape, size and grain-size are varied largely. These dark inclusions are considered to have been derived from basic schist-xenoliths, for a few of them preserve the original schistosity. However, most dark inclusions have been completely recrystallized into massive rocks with the same constituent minerals and texture as those of

the surrounding plutonic rocks, except the proportions of the minerals. The process of assimilation can be traced in the field and under the microscope. The first stage of assimilation is represented by dark-colored, fine-grained and non-porphyroblastic rocks composed mainly of plagioclase, biotite and hornblende with a small quantity of quartz. Thus, such rocks have minerals similar to those of the surrounding host rocks, though the proportion of mafic constituents to felsic ones being much larger than in the host. The composition of the plagioclase is the same as that of the host rocks. In the second stage, plagioclase porphyroblasts begin to appear in the interior of the inclusions, and the grain-size of the matrix becomes larger. The composition and feature of zoning of the plagioclase are similar to those of the surrounding host rocks. As the assimilation proceeds, the grain-size becomes coarser to be close to that of the host granodiorite, but the boundary between the host and dark inclusions remains sharp. As an example, a brief description of a dark inclusion in the second stage of assimilation is given below.

Dark inclusion (Specimen No. FS 56112815)

The host rock of this dark inclusion is hornblende-biotite-granodiorite. In the field, dark inclusions occupy about a third of the exposure. Their shapes are irregular with clear outlines. They do not show any fluxional arrangement.

Texture: fine-grained, non-schistose, with plagioclase porphyroblasts, showing granitic texture.

Chief const.: plagioclase (weakly zoned with a core=An_{41} and a margin=An_{37})>biotite (X=light-yellow, Y=Z=dark brown to nearly opaque), hornblende ($2V_X=53°$, X=pale yellow, Y=yellowish green, Z=emeraled-green)>quartz.

Accessory const.: apatite.

Chemical Analyses of Rocks from the Tabito Igneous Complex

Chemical analysis was carried out on eight specimens. Three of them are pyroxene-hornblende-gabbro, one is diorite, two are granodiorite and the remainning one is aplite. The results are shown in Table 2. The C.I.P.W. norms were calculated as shown in Table 3. Figures 4 and 5 represent the compositional variations of these rocks. The alkali-lime index as proposed by Peacock (1931) is 59.5.

In the diagram of Fig. 4, the rocks of the Tabito complex fall in an area distinct from the areas for the Skaergaard intrusion and also for the Garabal Hill-Glen Fyne complex, and are in the field of the calc-alkali rock series.

The petrography of analysed specimens Nos. 181, 226, 227, 229, 228 and 230 are given on p. 139, p. 141, p. 143, p. 143, p. 144 and p. 144 respectively. The description of No. 231 is given below:

No. 231: *Biotite-aplite* (Specimen No. FS 56112829)

This rock occurs as a dike intrusive into the biotite-hornblende-granodiorite, the width being about 10 m.

Texture: fine-grained, non-porphyritic.

Chief const.: quartz, microcline (showing magnificent quadrille twinning, $2V_X=78°$)>> plagioclase (showing normal zoning, An_{20-18})>>>biotite (partially altered into chlorite).

Accessory const.: apatite, muscovite.

Minerals of the Tabito Igneous Complex

(*a*) *Hornblendes*

The optic angle of hornblendes of the Tabito igneous complex is plotted against γ, with results shown in Fig. 6. Hornblendes of the gabbros, those of

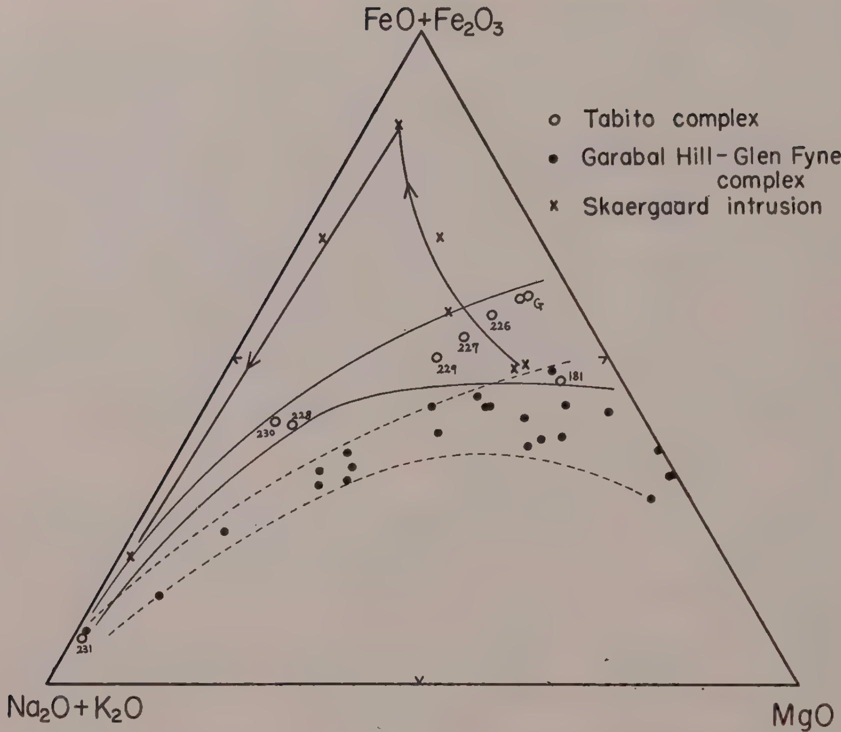

Fig. 4. Compositions of plutonic rocks of the Tabito igneous complex in comparison with those of the Skaergaard intrusion and Garabal Hill-Glen Fyne igneous complex.

Table 2. Chemical compositions of plutonic rocks of the Tabito igneous complex.

	G	181	226	227	229	228	230	231
SiO_2	43.38	47.68	46.82	49.58	52.52	63.69	62.80	75.75
Al_2O_3	20.86	17.49	18.21	20.17	17.07	17.48	18.91	14.19
TiO_2	0.17	0.55	1.57	0.99	0.83	0.28	0.26	0.02
Fe_2O_3	1.29	2.92	2.54	3.56	2.25	1.40	1.64	0.26
FeO	11.91	7.93	9.82	5.19	7.34	3.72	3.93	0.43
MgO	7.82	10.59	6.80	4.80	5.21	1.63	1.36	0.07
MnO	0.04	0.22	0.24	0.13	0.18	0.07	0.06	0.02
CaO	12.24	9.54	10.37	12.45	8.20	4.31	3.16	0.34
Na_2O	1.18	1.42	2.17	2.43	2.90	3.63	4.00	3.15
K_2O	0.03	0.47	0.28	0.30	1.34	2.36	2.58	5.07
$H_2O(+)$	0.70	1.60	0.92	0.58	1.62	0.90	0.82	0.36
$H_2O(-)$		0.10	0.25	0.15	0.15	0.17	0.15	0.27
P_2OO_5	n.d.	0.06	0.59	0.22	0.28	0.23	0.10	0.03
Total	99.62	100.57	100.58	100.55	99.89	99.87	99.77	99.96

The analyzed rocks:

G: Hornblende-gabbro (cortlanditic hornblende-gabbro) from Ogawa-mati, Nakoso City, Hukusima Prefecture. Analysed by Imp. Geol. Surv.; Quoted from M. GORAI (1944, p. 285).

No. 181: Augite-cummingtonite-orthopyroxene-hornblende-gabbro (Specimen No. FS 54 D 1) from Yamatama, Ogawa-mati, Nakoso City, Hukusima Prefecture. Analysed by Mr. H. HARAMURA.

No. 226: Augite-orthopyroxene-hornblende-gabbro (Specimen No. FS 54C3) from Hirasode,

Table 3. C.I.P.W. norms of the analysed plutonic rocks.

		G	181	226	227	229	228	230	231
Q		—	—	—	2.40	3.14	19.99	18.59	36.99
C		—	—	—	—	—	1.60	4.01	2.95
F	or	0.17	2.78	1.67	1.78	7.90	13.96	15.25	29.94
	ab	9.96	12.00	18.35	20.55	24.54	30.72	33.81	26.63
	an	51.54	40.00	39.10	43.25	29.62	20.05	15.10	1.39
P	wo	3.83	2.92	3.68	7.17	3.19	—	—	—
	en	1.84	1.91	1.97	4.66	2.10	—	—	—
	fs	1.54	0.82	1.59	2.02	1.69	—	—	—
	en	1.26	19.30	10.69	7.30	10.88	4.06	3.38	0.17
	fs	1.33	8.23	8.71	3.17	8.88	5.35	5.54	0.58
O	fo	11.48	3.62	3.00	—	—	—	—	—
	fa	13.38	1.69	2.69	—	—	—	—	—
M	mt	1.87	4.24	3.68	5.16	3.26	2.03	2.39	0.37
	il	0.32	1.35	2.99	1.88	1.58	0.54	0.49	0.05
Ap			0.14	0.34	0.17	0.24	0.17	0.07	0.03

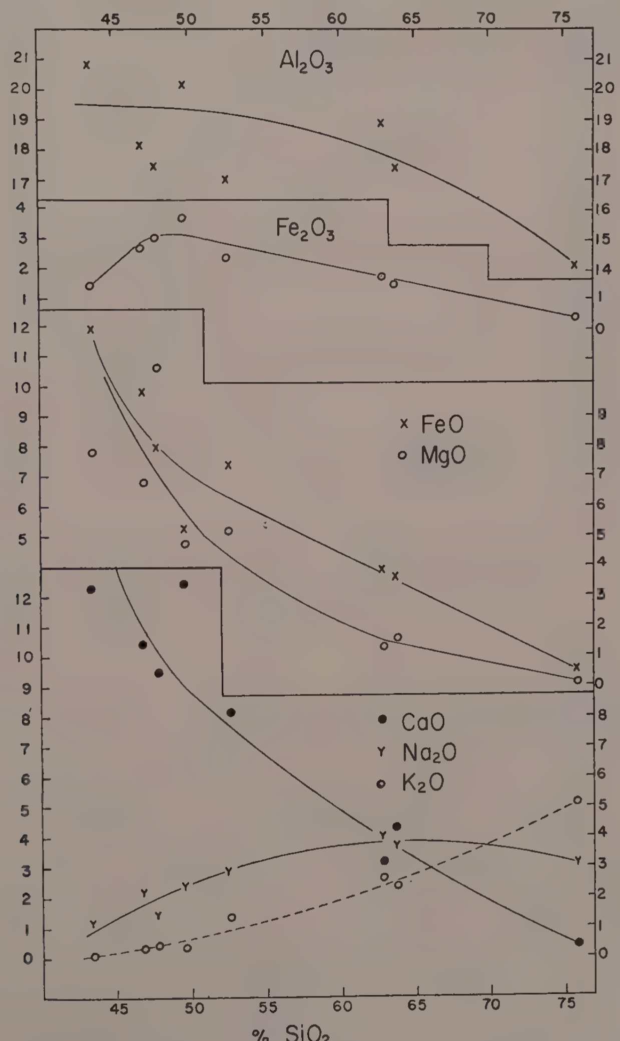

Fig. 5. Variation diagram of rocks of the Tabito igneous complex.

Sekimoto-mura, Taga-Gun, Ibaragi Prefecture. Analysed by Mr. H. HARAMURA.

No. 227: Orthopyroxene-cummingtonite-hornblende-gabbro (Specimen No. FS 56113010) from Hirasode, Sekimoto-mura, Taga-Gun, Ibaragi Prefecture. Analysed by Mr. H. HARAMURA.

No. 229: Biotite-hornblende-quartz-diorite (Specimen No. FS 56112834) from 2.5 km. west of Yamatama, Ogawa-mati, Nakoso City, Hukusima Prefecture. Analysed by Mr. H. HARAMURA.

No. 228: Hornblende-biotite-granodiorite (Specimen No. FS 56112814) from Minamiodaira, Ogawa-mati, Nakoso City, Hukusima Prefecture. Analysed by Mr. H. HARAMURA.

No. 230: Biotite-granodiorite (Specimen No. FS 56113023) from Saimaru, Sekimoto-mura, Taga-Gun, Ibaragi Prefecture. Analysed by Mr. H. HARAMURA.

No. 231: Biotite-aplite (Specimen No. FS 56112829) from 1.5 km. east of the top of Daimaru-yama, Iwaki-gun, Hukusima Prefecture. Analysed by Mr. H. HARAMURA.

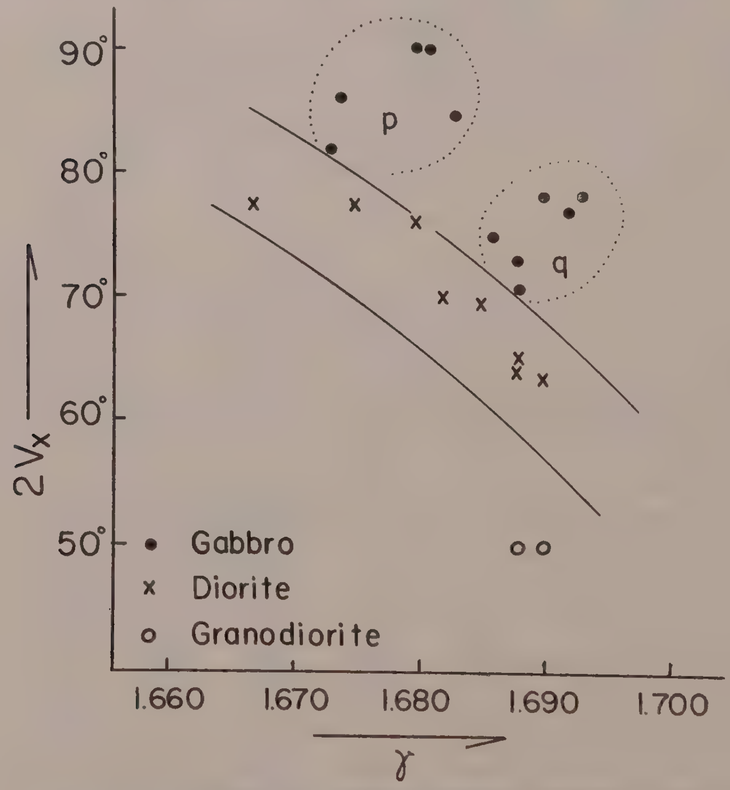

Fig. 6. Optical properties of hornblendes from the gabbros, diorites and granodiorites of the Tabito igneous complex.
The hornblendes of field *p* are generally associated with anorthite or bytownite and those of field *q* are associated with laboradorite.

the diorites and those of the granodiorites fall on tee fields distinct from one another. The optic angle of hornblendes becomes generally larger with increasing basicity of the host rocks.

(*b*) *Cummingtonites*

The occurrence of cummingtonite in diorite and gabbro has been reported only from a few regions. In the present igneous complex, however, it is one of the main and common constituent minerals of pyroxene-hornblende-gabbros and hornblende-gabbros. The optic properties of cummingtonites of these gabbros and chemical compositions determined therefrom are given in Table 4.

Table 4. Optical properties and chemical compositions of cummingtonites from the Tabito igneous complex.

Specimen No.	γ_D	$c \Lambda Z$	$2V_z$	$100 \times Mg/(Mg+Fe^{+2})$
FS 54C3	1.669		n.d.	56
FS 56113007	1.669		n.d.	56
FS 56113008	1.671		n.d.	54
FS 56113010	1.668	19°	73°	57
FS 56051201	1.669			56

As shown in the table, the $Mg \times 100/(Mg+Fe^{+2})$ ratios of cummingtonites are restricted within a fairly narrow range from 54 to 57. Cummingtonite is always accompanied by brown to brownish green hornblendes and sometimes by orthopyroxene.

Cummingtonite occurs in the following modes of occurrence: (1) The orthopyroxenes in some specimens are enclosed by cummingtonites which are in turn homoaxially embraced by common hornblendes. (2) In some specimens devoid of orthopyroxene, cummingtonites are homoaxially embraced by brown common hornblendes. (3) In some rocks, cummingtonites and brown hornblendes occur as separate individuals. These modes of occurrence may indicate that in the present igneous complex, orthopyroxene is the earlist mineral to have crystallized, cummingtonite the next, and brown hornblende the latest among the three.

(*c*) *Pyroxenes*

The optical properties of pyroxenes and the chemical compositions determined from them are given in Table 5.

Table 5. Optical properties and chemical compositions of clinopyroxenes and orthopyroxenes from the Tabito igneous complex.

Specimen No.	Clinopyroxene			Orthopyroxene			
	$2V_Z$	index.	comp.	$2V_X$	γ_D	disp.	comp.
FS 56112838	53°	n.d.	n.d.	—	—	—	—
FS 54D1	n.d.	n.d.	n.d.	62°	1.705	r>v	$En_{66}Fs_{34}$
FS 56112909	—	—	—	56°	n.d.	r>v	$En_{64}Fs_{36}$
FS 56113006	53.5°	n.d.	n.d.	56°	n.d.	r>v	$En_{64}Fs_{36}$
FS 54C3	n.d.	α=1.696	n.d.	48°	1.716	r>v	$En_{57}Fs_{43}$
FS 56113007	—	—	—	49°	1.715	r>v	$En_{58}Fs_{42}$
FS 56113008	n.d.	α=1.719	n.d.	n.d.	1.702	r>v	$En_{68}Fs_{32}$
FS 56113010	—	—	—	n.d.	1.715	r>v	$En_{58}Fs_{42}$
FS 56113012	48°	β=1.698	$Wo_{40}En_{37}Fs_{23}$	48°	1.715	r>v	$En_{58}Fs_{42}$

The Crystallization Temperature of the Tabito Igneous Complex

Features which cast some light on the crystallization temperatures of rocks of the present complex are as follows: (a) the character of the hornblendes, (b) the epidote-plagioclase paragenesis, (c) the character of the potash felspars, and (d) the metamorphic grade of the schists embraced by or lying in immediate contact with the present igneous complex.

(*a*) *Character of the hornblendes*

As will be mentioned in the chapter of the metamorphic minerals, the Z-axial color of the hornblende changes with marked regularity with the metamorphic

grade, regardless of the chemical compositions of the host rocks (basic, pelitic or psammitic). Then, character of hornblende is expected to be a good indicator of crystallization temperatures of the igneous rocks.

The Z-axial color of hornblende ranges from brown to light brown in the pyroxene-hornblende-gabbros, and from greenish brown to brownish green in the hornblende-gabbros. It is green in the diorites and blue green in the granodiorites. The correlation of plutonic rocks with metamorphic ones having hornblendes with similar colors is as follows:

Pyroxene-hornblende-gabbros Hornblende-gabbros	..............Zones C and/or D.
Diorites....................................	The transitional grade between zones C and B.
Granodiorites	The middle-grade part of zone B.

(*b*) *Epidote-plagioclase paragenesis*

Epidote occurs characteristically in hornblende-biotite-granodiorites and probably it is a primary mineral crystallized from the granodiorite magma. In the psammitic and pelitic metamorphic rocks similar to granodiorite in chemical composition, epidote occurs up to the lower-grade part of zone B.

The compositions of the plagioclases associated with epidote in hornblende-biotite-granodiorites are as follows:

Specimen No. FS 56112819	33–35 % An.
Specimen No. FS 56112814	37–40 % An.

These plagioclases show weark normal zoning. The plagioclase-epidote paragenic relations in the granodiorites correspond to those in the lower-grade part of zone B as shown by the curve of Fig. 17 determined for the metamorphic rocks of the present district.

(*c*) *Character of the potash felspars*

As will be shown in the chapter of the metamorphic minerals, there is a close relation between the optic angle of potash felspars and their triclinicity determined by the X-ray method, and the optic angle of potash felspars of the metamorphic rocks decreases with increasing grade of metamorphism; it is 51°–53° in zone C and the transitional area between zones C and B, and about 64° in the middle-grade part of zone B.

The optic angles of the potash felspars from plutonic rocks of the present complex are as follows:

	$2V_x$
Biotite-hornblende-granodiorite (Specimen No. FS 56112819)	62°
Biotite-hornblende-granodiorite (Specimen No. FS 56112814)	63°
Biotite-granodiorite (Specimen No. FS 56113023)	66°
Biotite-granodiorite (Specimen No. FS 56113026)	66°
Aplite intrusive into gabbro (Specimen No. FS 56051203)	72°
Aplite intrusive into granodiorite (Specimen No. FS 56112821)	77°
Aplite intrusive into granodiorite (Specimen No. FS 56112829)	78°

These potash felspars are devoid of zonal structure, differing in this point from potash felspars of the metamorphic rocks. Quadrille twinning is clearly observed in the potash felspars with $2V=66°$ or more. According to O. F. TUTTLE (1952), the optic angle of each modification of alkali felspars becomes larger with the increase of the Na/K ratio. In this case, however, it is unlikely that more acidic members have potash felspars with larger Na/K ratios than those of more

basic members. Then, the difference in the optic angle of potash felspars is taken as representing the difference in structural state due to the crystallization temperatures of their host rocks.

Judging from these optic angles of potash felspars, the solidification temperature of biotite-granodiorites corresponds to the middle-grade part of zone B. The solidification temperature of biotite-hornblende granodiorites appears to be slightly higher than that of biotite-granodiorites poor in or devoid of hornblende. The temperature of aplites is still lower than that of the granodiorites.

(*d*) *Metamorphic grade of the schists enclosed by or lying in immediate contact with the igneous complex*

The basic metamorphic rocks adjacent to the pyroxene-hornblende-gabbros carry orthopyroxene, which characterizes zone D, the highest grade of metamorphism in this district. Xenoliths containing orthopyroxene are confined to the pyroxene-hornblende-gabbros. Accordingly, the crystallization temperature of the pyroxene-hornblende-gabbros corresponds to that of zone D. On the other hand, xenoliths within the diorites, or metamorphic rocks adjacent to the diorites carry hornblende with a color corresponding to the transitional grade between zones C and B, whereas schists in direct contact with the granodiorites carry hornblende characteristic of zone B.

(*e*) *Discussion*

All the features so far enumerated, indicate the following correspondence in crystallization temperature between plutonic and metamorphic rocks:

Typical pyroxene-hornblende-gabbros	Zone D.
Typical hornblende-gabbros	Zone C.
Typical diorites	The transional grade between zones C and B.
Typical granodiorites	The middle-grade part of zone B.
Aplites	The lower-grade part of zone B, and zone A.

The temperatures estimated from the four features above mentioned are in harmony with each other. In the granodiorites, however, the temperature estimated from the paragenic relation between the plagioclase and epidote is slightly lower than that estimated from the characters of the hornblende and potash felspar. This may possibly be attributed to higher water pressures of the granodiorite magma than those of the metamorphic rocks during the metamorphic recrystallization. Higher water pressure favors the formation of epidote instead of anorthite molecule of plagioclase and therefore the composition of plagioclase coexisting with epidote becomes more sodic under higher water pressures.

The above correlation in crystallization temperature clearly shows that *the crystallization temperature of plutonic rocks becomes regularly higher with increasing bisicity. This fact gives a support to the view that the Tabito igneous rocks have resulted from the crystallization of magmas and not from the granitization process that does not involve any melting of rocks.* Moreover, probably the later stages of the cooling history of the igneous rocks themselves and the regional metamorphism which was probably declining at the time of the emplacement of the igneous complex did not have any remarkable effect on the mineral assemblages or mineralogical characters of the plutonic rocks. Hence, *the present*

mineralogy of the igneous rocks probably represents approximately the physical conditions under which the magmas consolidated.

Generally, the range of crystallization temperature of a plutonic rock seems to be rather narrow. For example, in the granodiorites of the district, the texture shows that the hornblendes were the first to crystallize, whereas the potash felspars were the last. Both minerals, however, represent the same grade, zone B. Then, I would be able to give the following pictures: Various magmas, basic, intermediate and acidic, intruded into the present position. With falling temperature, the magmas crystallized, until the residual liquid was used up. During the crystallization the cooling was probably slow, because the latent heat emitted from the precipitating crystals would have counteracted the heat lost from the plutonic mass by conduction. The metamorphic rocks in immediate contact with the igneous complex appear to have acquired the present mineralogical features during the slow cooling of the igneous rocks. When the residual liquid was used up, the counteraction by the latent heat of crystallization must have stopped and the temperature of the solidified rock must have begun to fall more rapidly than before. Thus, later changes they suffered are practically negligible.

Next, I will discuss what are the differences between the metamorphic and the plutonic igneous conditions. The igneous rock is characterized by derivation from molten magma, whereas the metamorphic rock by recrystallization in a solid state.

The granodiorites, for example, probably had enough liquid phase during the emplacement into the district and still had a liquid phase until the temperature fell to the grade of zone B. On the other hand, the psammitic or pelitic metamorphic rocks similar in composition to the granodiorites appear to have been in a solid state at such and somewhat higher temperatures. What is the cause of this difference ? The conditions which control the melting of rocks are, temperature aside, the chemical composion, total pressure, and the pressures of volatile constituents. In this case, the chemical composition as regards the main rock-forming metal oxides is similar in both igneous and metamorphic rocks. Under the plutonic conditions, the total pressure of a magma is perhaps the same as that of the adjacent metamorphic rocks. Thus, the difference between the conditions attending the igneous-rock formation and the metamorphism must be in the concentrations of some volatiles——that is, the concentration of volatiles must be much higher in the magma than in the metamorphic rocks during the metamorphic recrystallization.

That the crystallization temperature of the complex was low appears to merit attention. The crystallization temperatures of the granodiorites correspond to the middle-grade part of zone B which probably corresponds to the lower-grade part of the amphibolite facies, as will be discussed later. Then, the crystallization temperatures of the granodiorites would be about 400°C, which is far lower than generally accepted for the granitic magma.

3. Metamorphic Rocks

General Statement

(1) *Original rocks*

The metamorphic rocks of the present district have been derived mainly from basic igneous materials along with subordinate amounts of psammitic, pelitic

and calcic rocks. In rough estimation, basic rocks make up two thirds of the metamorphic complex, and psammitic rocks together with pelitic ones most of the rest. Calcic rocks are scarce, and occur as thin lenses and bands intercalated in basic and psammitic rocks. The thickness of the lenses and bands are usually less than 10 cm. and rarely reaches 200 cm. Most, at least, of the basic schists were probably derived from basic tuffs, though part of them may be from lava flows. The following observations suggest that they have been derived from basic tuffs: (i) basic schists alternate with pelitic and psammitic schists in concordant relation. (ii) Neither relict mineral nor relict texture suggesting their dike- or lava-origin was found, even in the lowest-grade zone. (iii) Calcic schists may represent original calcareous sediments intercalated with basic tuffs or psammitic sediments.

(2) *Structure*

Bedding planes trend nearly NS with nearly vertical dips. The schistosity planes are parallel to the bedding planes. The axes of microfolds are parallel to the lineation represented by the parallel arrangement of prismatic amphiboles. The lineations of the present metamorphic rocks dip 45° to the south within the schistosity planes. Microfolding and lineation are well developed in lower-grade zones, but they become obscure in higher-grade zones. The lineation does not seem to have been disturbed by the intrusions of the igneous masses.

(3) *Basis of zonal mapping*

The basic metamorphic rocks contain calciferous amphiboles as a main constituent. The Z-axial color of the calciferous amphiboles changes very sensitively with increasing grade of metamorphism. By the appearance in trun of amphiboles having particular Z-axial colors and the appearance of orthopyroxene, I could distinguish four zones of progressive metamorphism and locate their boundaries with precision on the geologic map as shown in Fig. 7. These four zones in the increasing order of metamorphic grades are as follows:

Zone A: This zone is characterized by the presence of actinolite, having colorless to very pale green Z-axial color.

Zone B: This zone is characterized by the presence of common hornblendes having blue-green Z-axial color (ranging from bluish green to greenish blue). In basic schists of the highest-grade part of zone A and the lowest-grade part of zone B, actinolite and common hornblende with blue-green Z-axial color coexist in equilibrium as will be mentioned later. I have settled the boundary between zones A and B in the place where blue-green hornblende becomes roughly equal to actionlite in amount, although the belt where the two amphiboles coexist is as narrow as about 100 m. in width and paractically negligible on the geologic map. In general the color is deeper in the mineral of the middle- and higher-grade part of zone B.

Zone C: This zone is characterized by the presence of common hornblendes having green or brown Z-axial color. The disappearance of blue tinge in hornblende marks the entrance to zone C. Hornblendes with green Z-axial color occur generally in lower grades than those with brown color.

Zone D: This zone is characterized by the appearance of orthopyroxene. The common hornblendes in this zone have a brown Z-axial color similar to that in the preceding zone.

The Nakoso metamorphic area represents the southern extension of the Gosaisyo-Takanuki regional metamorphic terrain. A. MIYASHIRO (1958) has carried out the zonal mapping of the Gosaisyo-Takanuki district on the basis of the same

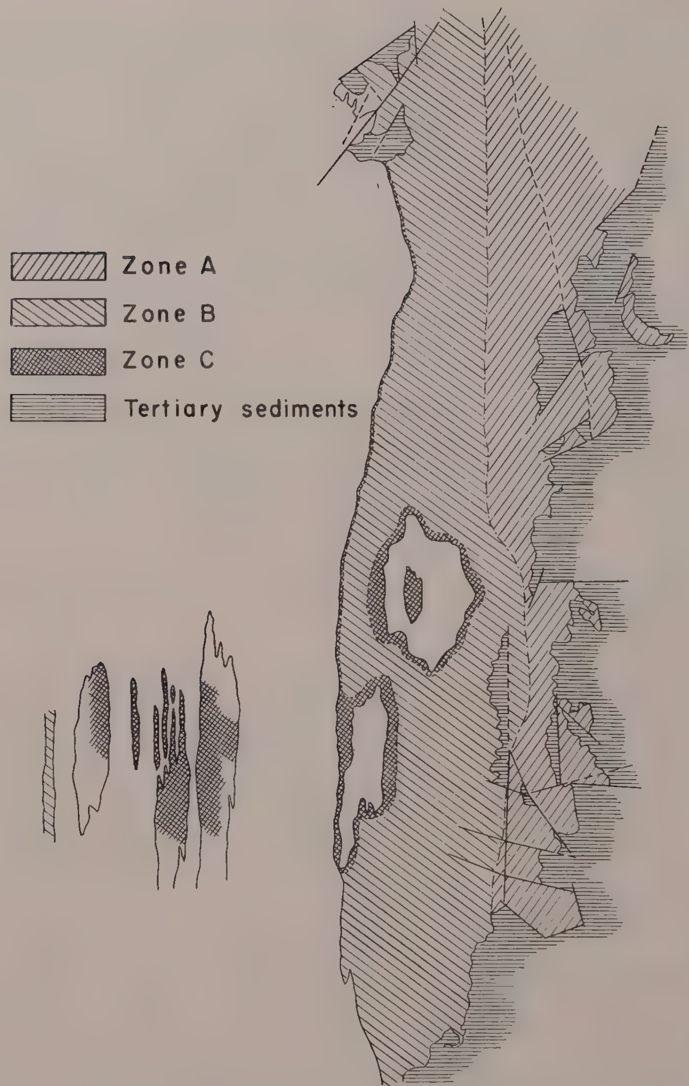

Fig. 7. Zones of progressive metamorphism in the Nakoso district.

definitions of metamorphic zones. The Gosaisyo-Takanuki district shows only three zones A, B and C in a much larger scale. (Zone D is lacking.)

Then, his results will be referred to repeatedly. Our two studies jointly are intended to clarify all the main petrological and mineralogical features of the regional metamorphism in the central Abukuma Plateau.

Distributions of the Metamorphic Zones

The distribution of these metamorphic zones is shown in Fig. 7. Zone D forms narrow belts, about 25 m. in width, in immediate contact with the gabbro masses En and Es. The belts of zone D are too narrow to be shown in the figure. Zone C forms belts, up to 250 m. in width, outside the belts of zone D. In addition, the schists in the narrow area, about 50 m. wide, adjacent to the diorites in the eastern portion of W mass belong to the lowest-grade part of

zone C. Besides them, amphibolite masses which are enclosed in gabbroic rocks of the W mass in the vicinity of Hatatate-toge also belong to zone C.

Zone B is the most extensive, forming a wide belt stretching in the NS direction. Zone A lies to the east of zone B and its eastern extension is covered by Tertiary sediments. The boundary between zones A and B appears to have been affected by the thermal effect of the plutonic masses. Thus, in the central part of the district, the boundary bulges to the east owing to the presence of the En and Es gabbroic masses.

The boundary between zones A and B in this district extends northerly in NS direction to the Gosaisyo-Takanuki district.

Petrology of Metamorphic Rocks

For description, the metamorphic rocks are divided, according to their chemical compositions, into three groups: (1) basic, (2) calcic and (3) psammitic and pelitic. Calcic rocks include those which fall within the anorthite-diopside-C triangle of the ACF diagram.

1. Zone A

This zone is characterized by the predominance of actinolite among the calciferous amphiboles in basic rocks.

(1) *Basic Rocks*

In basic rocks of the lower-grade parts of zone A, the chief constituent minerals are actinolite, chlorite, epidote and plagioclase. The plagioclase is albite, the occurrence of which is also characteristic of this zone together with the presence of fairly large amount of chlorite. Chlorite is usually less abundant than actinolite, and the chlorite zone that is marked by the absence of actinolite does not exist in the present district. Even in the lower-grade part, the metamorphic recrystallization is complete, neither relict mineral nor relict texture of igneous rock having been observed. The actinolite is generally fibrous. The amount of plagioclase is very small. In the present district, the lower-grade part of zone A is exposed in a narrow area, and possibly extends eastward under the cover of the Tertiary sediments.

In basic rocks of the higher-grade part of this zone, blue-green hornblende occurs in association with actinolite, though the amount of the former never exceeds that of the latter in zone A. In the higher-grade part, the plagioclase coexisting with epidote is sodic oligoclase, and chlorite is less abundant than in the lower-grade part. In this grade also, the amphiboles are generally fibrous and the plagioclase is very little in amount.

Mineral assemblages observed are as follows:

(a) Chlorite-actinolite-epidote-albite with or without quartz.
(b) Chlorite-actinolite-blue-green hornblende-epidote-sodic plagioclase with or without quartz.
(c) Actinolite-blue-green hornblende-epidote-sodic plagioclase with or without quartz.
(d) Chlorite-actinolite-blue-green hornblende-sodic plagioclase-quartz.

Type (a) represents lower grade than the others. The commonest order of abundance of minerals in type (a) is actinolite$>>$epidote, chlorite$>>$quartz, albite, opaque mineral. The rocks belonging to type (b) are much more abundant than those belonging to types (c) and (d). The commonest order of abundance of minerals in type (b) is two amphiboles$>>>$epidote, chlorite,

quartz, sodic plagioclase, opaque mineral. All the assemblages mentioned above may contain opaque mineral and rarely accompanied by a small amount of biotite.

(2) *Calcic Rocks*

Calcic rocks occur as thin lenses and bands in basic rocks. The chief constituent minerals are calcite and epidote along with large or small amounts of sodic plagioclase, quartz, chlorite and actinolite.

Mineral assemblages observed are as follows:

(a) Calcite-epidote-actinolite-chlorite-sodic plagioclase.
(b) Calcite-epidote-sodic plagioclase.
(c) Calcite-quartz.
(d) Calcite-actionalite-sodic plagioclase-quartz-opaque mineral, sometimes accompanied by a small amount of biotite.

Even in the higher-grade part of zone A where bluish green hornblende is associated usually with actinolite in basic rocks, the amphibole of calcic rocks is actinolite only and thus the appearance of common hornblende is delayed in these rocks.

(3) *Pelitic and Psammitic Rocks*

The chief constituent minerals are quartz, biotite and albite. Muscovite and chlorite are also main constituents of some specimens. The muscovite-chlorite assemblage without biotite has not been observed in the district. Biotite is one of the chief constituent minerals even in the lower-grade part of zone A.

Mineral assemblages observed are as follows:

(a) Quartz-albite-biotite-hematite.
(b) Quartz-albite-biotite-chlorite.
(c) Quartz-albite-biotite-muscovite-chlorite.

All the above assemblages may contain graphite and tourmaline.

Mineral assemblages of rocks of zone A are shown in the ACF diagram of Fig. 8, as proposed by P. ESKOLA. Quartz, alkali felspars and some accessory

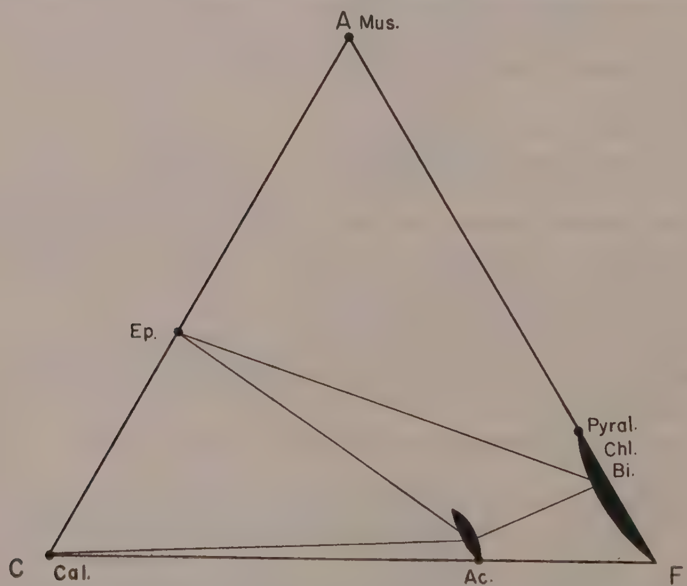

Fig. 8. ACF diagram for metamorphic rocks of zone A with excess SiO_2. Ep.=epidote, Cal.=calcite, Mus.=muscovite, Pyral.=pyralspite, Chl.=chlorite, Bi.=biotite, Ac.=actinolite.

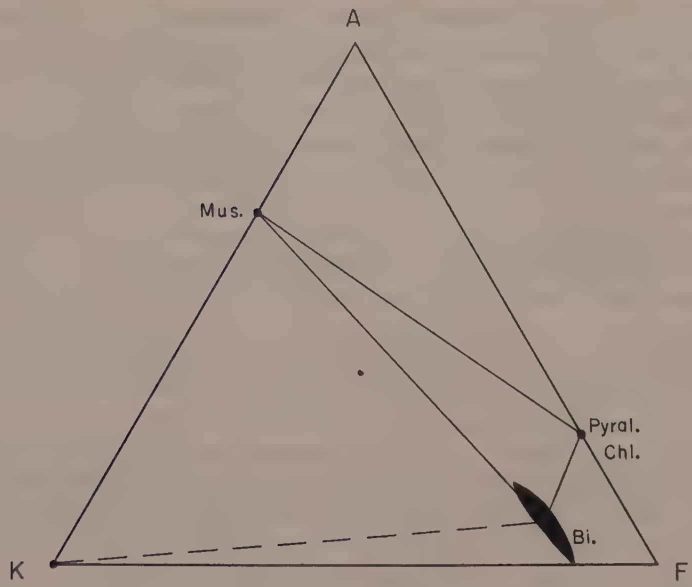

Fig. 9. AKF diagram for pelitic and psammitic rocks of zone A.

minerals are not shown. The AKF diagram for the pelitic and psammitic rocks of zone A is shown in Fig. 9.

2. Zone B

This zone is characterized by the predominance of blue-green hornblende among the calciferous amphiboles in basic rocks, and is distinguished from zone C by the absence of green and brown hornblendes without bluish tinge.

(1) *Basic Rocks*

Though blue-green hornblende is abundant, actinolite usually coexists with it in the lowest-grade part of this zone. Chlorite is present in a small amount in some specimens from the lower-grade part of zone B. In some rocks, epidote also persists to the middle-grade part of this zone. The plagioclase is oligoclase or andesine in the lowest-grade part, but in the middle- and higher-grade parts, it is usually labradorite, sometimes reaching bytownite. Probably, the An content of plagioclase in such high grades depends merely on the composition of the host rocks. The grains are larger than in zone A. The hornblende is fibrous in the lowest-grade part of zone B, but in the higher-grade part it is prismatic and well shaped, though still slender. Zonal structures of plagioclase and amphibole are characteristic of this zone. Most plagioclases show zonal structure with a more calcic rim throughout this zone. Zonal structure of amphibole with an actinolite core and blue-green hornblende rim is commmonly observed up to the middle-grade part, though very rarely to the higher-grade part of this zone.

Mineral assemblages observed are as follows:

(a) Chlorite-actinotite-blue-green hornblende-muscovite-epidote-plagioclase with or without quartz.

(b) Chlorite-actinolite-blue-green hornblende-epidote-plagioclase with or without quartz.

(c) Chlorite-blue-green hornblende-biotite-plagioclase with or without quartz.

(d) Actinolite-blue-green hornblende-epidote-plagioclase with or without quartz.

(e) Blue-green hornblende-biotite-epidote-plagioclase with or without quartz.
(f) Blue-green hornblende-epidote-plagioclase with or without quartz.
(g) Blue-green hornblende-sphene-epidote-plagioclase.
(h) Blue-green hornblende-plagioclase with or without sphene and quartz.
(i) Blue-green hornblende-clinopyroxene-epidote-plagioclase.
(j) Blue-green hornblende-clinopyroxene-plagioclase with or without biotite and quartz.
(k) Blue-green hornblende-tourmaline-plagioclase-quartz.

All the above assemblages may contain opaque mineral.

The first three types, having chlorite and/or actinolite, are confined to the lower-grade part.

Especially, rocks of type (a) have been rarely found only from the lowest-grade part of zone B. Specimen FS54E22 is a typical example of this type, and is composed of amphiboles together with a subordinate amount of fine-scaly muscovite and much smaller amounts of epidote, chlorite and plagioclase. The Na_2O and K_2O contents of the specimen are 2.04 and 1.22 percent by weight, respectively. The K_2O content is higher than those of ordinary basic rocks in the district. The assemblage calciferous amphibole-muscovite would be transformed to the assemblage biotite-plagioclase in higher grades.*

Types (e), (f), (g) and (i) in which epidote is present are observed in the lower half. Types (i), (j) and (k) are rarely observed in zone B. (Type (k) is rich in quartz and may not belong to the category of basic rocks.)

(2) *Calcic Rocks*

The chief constituent minerals are clinopyroxene, grandite garnet, calcite, epidote, sphene and plagioclase. Clinopyroxene begins to appear from the lowest-grade part of zone B, and grandite begins to appear from the grade slightly lower than the middle of zone B. Epidote is present in most rocks throughout this zone, although in the higher-grade part of zone B, it may have been formed by retrogressive change. Grandite in calcic rocks is not in contact with calciferous amphibole of the adjacent basic rocks; always clinopyroxene or epidote (or plagioclase) or both is present between them. (If grandite had been formed at a lower grade than clinopyroxene, the grandite in such a low grade might have coexisted side by side with calciferous amphibole.) Grandite, if any, always occurs in the core of calcic lenses and bands, and sphene, in fairly large crystals in this zone, sometimes takes the place of grandite. Calcic lenses and bands commonly show zonal arrangement of minerals. An example of zonal structure (FS54E10) is shown in Fig. 10. This specimen is composed of four zones, each of which is characterized by a particular mineral assemblage: zone (1) is composed of calcite and grandite, zone (2) is composed of calcite, clinopyroxene and plagioclase, and zone (3) is composed of clinopyroxene and plagioclase. Zone (4), representing the surrounding am-

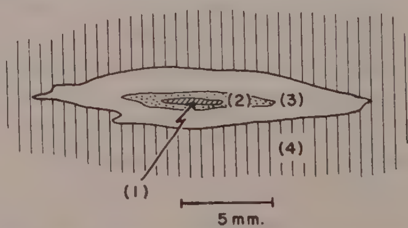

Fig. 10. Zonal arrangement of minerals in a calcic lens within the basic rock FS54E10 from zone B. (1) calcite+grandite, (2) calcite+clinopyroxene+plagioclase, (3) clinopyroxene+plagioclase, (4) hornblende+plagioclase.

* J. D. H. WISEMAN (1934) also noticed that muscovite occurs sporadically in some chlorite-epidote-albite-amphibolites of the biotite zone of the Grampian Highlands, but it never occurs in basic rocks of the garnet and higher-grade zones.

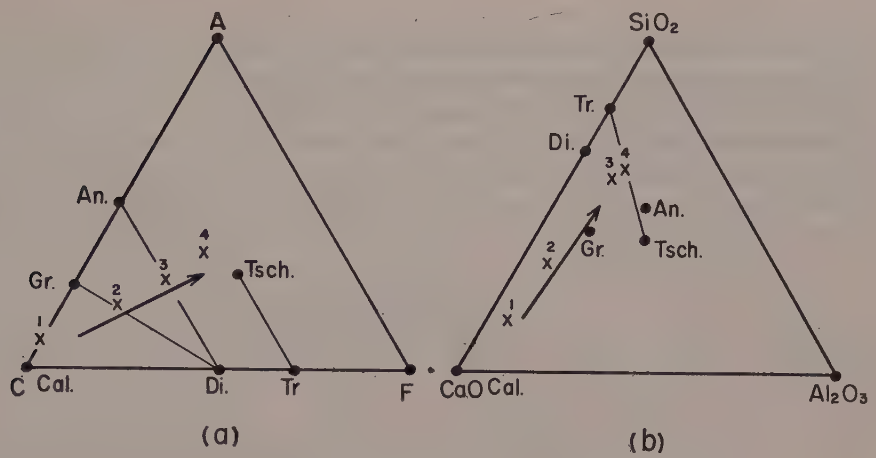

Fig. 11. Diagrams representing the compositional variation from the core to the margin of the calcic lens shown in Fig. 10. An.=anorthite, Gr.=grandite, Cal.=calcite, Di.=diopside, Tsch.=tschermakite, Tr.=tremolite.

phibolite, is composed of hornblende and plagioclase. The compositions of these zones and the surrounding amphibolite are plotted on a ACF diagram and SiO_2–CaO–Al_2O_3 diagram as shown in Fig. 11, respectively. These figures show clearly a chemical gradation from core to margin.

Mineral assemblages observed are as follows:

(a) Calcite-grandite-clinopyroxene with or without epidote.
(b) Calcite-grandite-clinopyroxene-plagioclase-microcline-quartz with or without epidote.
(c) Calcite-sphene-plagioclase with or without hornblende.
(d) Calcite-sphene-clinopyroxene-plagioclase-hornblende-opaque mineral.
(e) Calcite-epidote-sphene-plagioclase-quartz-opaque mineral.
(f) Calcite-biotite-quartz with or without hornblende.

(3) *Psammitic and Pelitic Rocks*

The chief constituent minerals are muscovite, biotite, pyralspite, plagioclase and quartz. Microcline is in a very small amount, if any, filling interstices between quartz and plagioclase grains. Andalusite was found in highly aluminous schists in the higher- and middle-grade parts of this zone. However, the mineral would occur also in a lower grade, if there were rocks of appropriate chemical compositions. Andalusite of this zone is always changed completely or partly from its margin into an aggregate of small muscovite flakes. It is not clear whether andalusite coexisted with potash felspar in equilibrium or not in the grade of zone B, as potash felspar has not been observed near the andalusites.

Mineral assemblages observed are as follows:

(a) Quartz-plagioclase-biotite-muscovite.
(b) Quartz-plagioclase-biotite-tourmaline.
(c) Quartz-plagioclase-biotite-potash felspar.
(d) Quartz-plagioclase-biotite-muscovite-potash felspar.
(e) Quartz-plagioclase-biotite-muscovite-potash felspar-andalusite.
(f) Quartz-biotite-muscovite.
(g) Quartz-biotite-muscovite-potash felspar-tourmaline.
(h) Quartz-biotite-hornblende with or without a small amount of calcite.
(i) Quartz-plagioclase-pyralspite-muscovite.

(j) Quartz-plagioclase-pyralspite-cordierite-biotite.
(k) Quartz-pyralspite-biotite-hornblende.
(l) Quartz-pyralspite-biotite-hornblende-potash felspar.
(m) Plagioclase-pyralspite-biotite-muscovite.

The cordierite-bearing rock of type (j) was found only at one locality belonging to the higher-grade part of this zone.

Mineral assemblages of rocks of zone B are shown in the ACF diagram of Fig. 12.

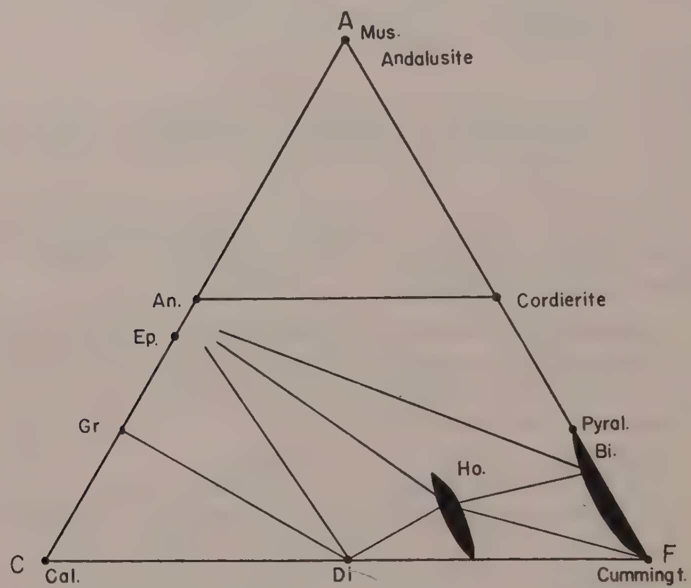

Fig. 12. ACF diagram for metamorphic rocks of zone B with excess SiO_2. An.=anorthite, Gr.=grandite, Ho.=hornblende, Cummingt.=cummingtonite, Di.=diopside.

In the transition from zone A to B, probably the assemblages actionlite+albite, actinolite+albite+chlorite, and actinolite+chlorite+epidote have reacted to produce common hornblende+calcic plagioclase+quartz+water. (These reactions will be discussed later.)

Clinopyroxene of calcic rocks may have been formed by the reactions:

Actinolite + Calcite + Quartz $\longrightarrow$ Clinopyroxene + CO_2 + H_2O

Common hornblende + Calcite + Quartz $\longrightarrow$ Clinopyroxene + Plagioclase (or epidote) + CO_2 + H_2O

As regards the appearance of grandite in this zone, the following reactions may be responsible:

Common hornblends + Calcite + Quartz $\longrightarrow$ Clinopyroxene + Grandite + Plagioclase + CO_2 + H_2O

Epidote + Calcite + Quartz $\longrightarrow$ Grandite + CO_2 + H_2O

3. Zone C

This zone is distinguished from zone B by the presence of green to brown hornblende without bluish tinge and from zone D by the absence of orthopyroxene in basic rocks.

(1) *Basic Rocks*

The chief constituent minerals are hornblende, plagioclase and clinopyroxene.

Cummingtonite is not uncommon in basic rocks of zone C. Quartz and biotite are fairly abundant in some basic schists. The Z-axial colors of hornblende changes regulary with metamorphic grade within zone C. Green color without bluih tinge marks the entrance to this zone, greenish brown one characterizes the middle-grade part and brown one without greenish tinge characterizes the higher-grade part. The plagioclase is usually labradorite or bytownite. The plagioclase does not show zonal structure in zone C. The texture becomes granulitic, as the hornblende prisms become shorter and more stout than in zone B.

Clinopyroxene is much more abundant in basic rocks of this zone than in those of zone B. The clinopyroxenes commonly occur in lenses or bands (usually without grandite) in basic rocks. Probably these lenses or bands correspond to calcic lenses or bands in the preceding zone, though they do not contain grandite (nor calcite). Probably, more activated diffusion at elevated temperatures that prevailed in this zone promoted the reaction between grandite (or calcite) and nearby common hornblende to produce clinopyroxene and plagioclase.

Mineral assemblages observed are as follows:

(a) Hornblende-plagioclase-clinopyroxene with or without quartz.
(b) Hornblende-plagioclase-sphene with or without quartz.
(c) Hornblende-plagioclase with or without quartz.
(d) Hornblende-plagioclase-biotite with or without quartz.
(e) Hornblende-plagioclase-cummingtonite-quartz.

All the above assemblages may contain opaque mineral and apatite. Type (e) occurs sporadically in this zone. All the other rock types are very common.

(2) *Calcic Rocks*

The chief constituent minerals are clinopyroxene, plagioclase and grandite. Sphene is abundant in some calcic rocks. Calcite and grandite are much less abundant than in zone B. Wollastonite was found from the highest-grade part of this zone or the transitional grade to zone D.

Mineral assemblages observed are as follows:

(a) Wollastonite-sphene-grandite-clinopyroxene.
(b) Sphene-grandite-clinopyroxene-plagioclase-potash felspar.
(c) Sphene-clinopyroxene-plagioclase.
(d) Cinopyroxene-grandite-plagioclase with or without quartz.
(e) Clinopyroxene-plagioclase.

(3) *Psammitic and Pelitic Rocks*

The chief constituent minerals are quartz, biotite, almandine, muscovite, potash felspar and plagioclase. Potash felspar becomes abundant from the lower-grade part of this zone, though it is scarce in the preceding zone. In highly aluminous rocks, andalusite and corundum occur sporadically. Such highly aluminous rocks are restricted to the lower-grade part of zone C. (If such rocks had been present in higher grades, sillimanite might have been formed in them.) In zone C, alteration of andalusite into muscovite has not been noticed, and it suggests that andalusite and potash felspar can coexist in equilibrium in this grade.

Mineral assemblages observed are as follows:

(a) Quartz-plagioclase-biotite-potash felspar.
(b) Quartz-plagioclase-biotite-potash felspar-sphene.
(c) Quartz-plagioclase-potash felspar-sphene.
(d) Plagioclase-potash felspar-andalusite-corundum-biotite-muscovite.

All the above assemblages may contain small amounts of tourmaline, apatite, and zircon.

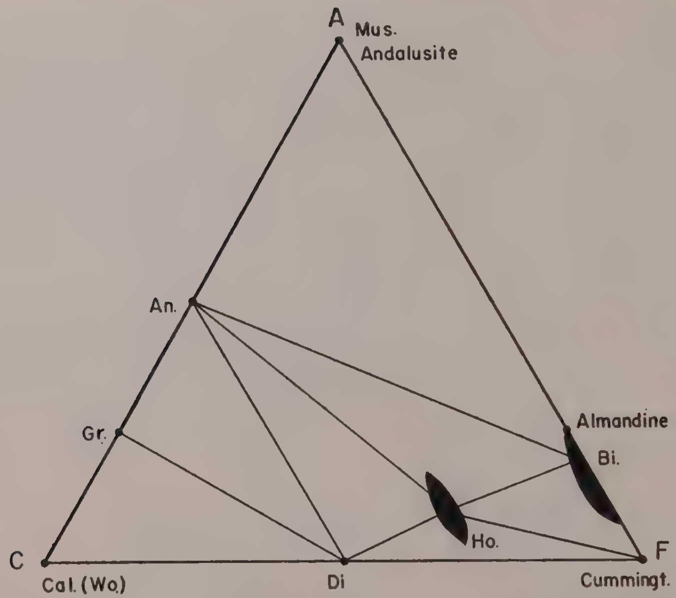

Fig. 13. ACF diagram for metamorphic rocks of zone C with excess SiO_2. Wo.=wollastonite. Wollastonite was found only from a transitional part between zones C and D, and so is parenthesized.

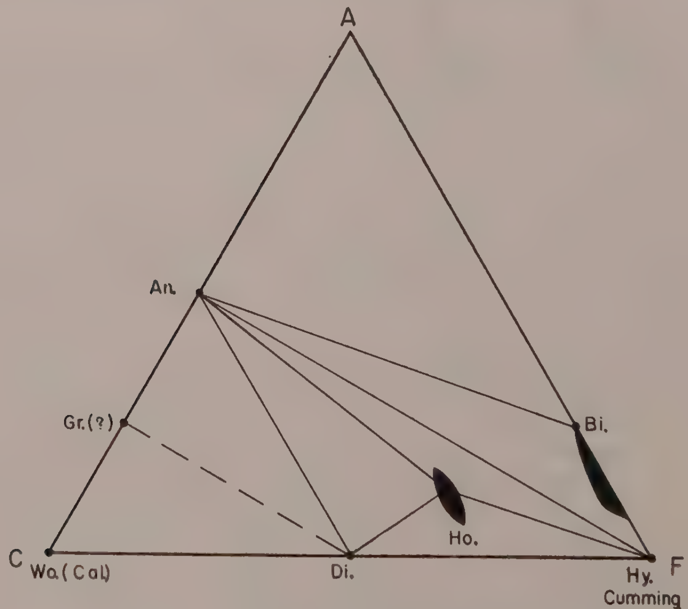

Fig. 14. ACF diagram for basic and calcic rocks of zone D with excess SiO_2. Hy.=orthopyroxene.

Mineral assemblages of rocks of zone C are shown in the ACF diagram of Fig. 13.

In zone C, the following reaction may take place:

$$\text{Calcite} + \text{Quartz} \longrightarrow \text{Wollastonite} + CO_2$$

The occurrence of corundum may be due to the following reaction:

$$\text{Muscovite} \longrightarrow \text{Corundum} + \text{Potash felspar} + H_2O$$

4. Zone D

This zone is characterized by the entrance of orthopyroxene. This zone is as narrow as about 25 m. in width and contains only basic rocks. The chief constituent minerals of the basic rocks are plagioclase, brown hornblende, orthopyroxene and clinopyroxene. Cummingtonite and biotite occur frequently. Brown hornblende is a chief member of every assemblage.

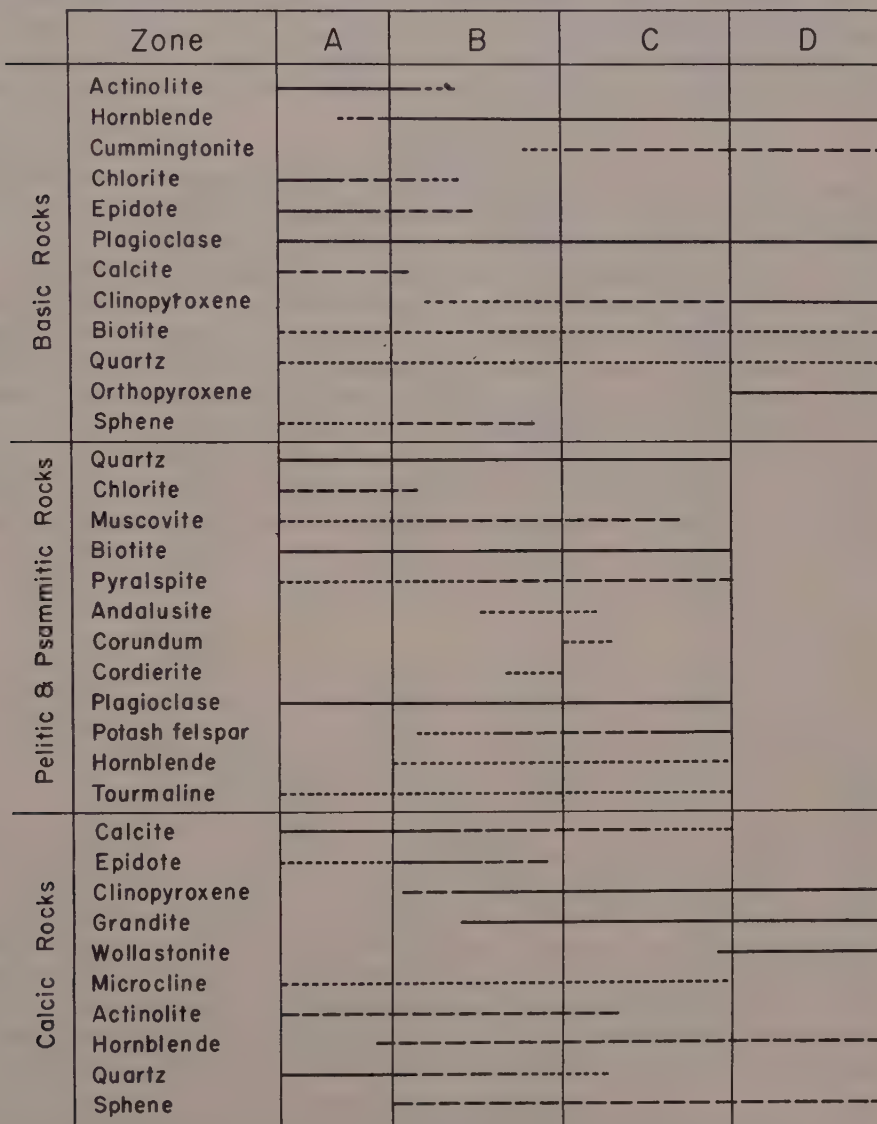

Fig. 15. Mineralogical variations with increasing grade of metamorphism in rocks of the Nakoso district. A full line indicates that the mineral concerned is very abundant and common, a broken line indicates that it is less abundant but not uncommon, and a dotted line indicates that it is in a small amount and common or rare.

Mineral assemblages observed are as follows:
(a) Hornblende-orthopyroxene-plagioclase.
(b) Hornblende-orthopyroxene-clinopyroxene-plagioclase.
(c) Hornblende-orthopyroxene-clinopyroxene-cummingtonite-plagioclase.
(d) Hornblende-orthopyroxene-biotite-plagioclase.
(e) Hornblende-orthopyroxene-cummingtonite-plagioclase.

Mineral assemblages of basic rocks of zone D are shown in the ACF diagram of Fig. 14. Grandite and wollastonite are probably stable in this zone, if calcic rocks are present. Then, the two minerals are also plotted in the figure.

The appearance and disappearance of minerals with increasing grade of metamorphism are summarized in Fig. 15.

Minerals of Metamorphic Rocks

Plagioclase

Plagioclase is one of the chief constituents of basic, calcic and pelitic metamorphic rocks. Plagioclase is usually little in amount in zone A and the lowest-grade part of zone B, and becomes abundant in the higher grades.

Grain-size and twinning: The plagioclase grains become larger fairly regularly with advancing metamorphism. Fig. 16 represents schematically the relation between the average grain-size of the plagioclases in ordinary basic rocks and the metamorphic grade. Similar enlargement of plagioclase grains with advancing metamorphism was observed in the Gosaisyo-Takanuki district (MIYASHIRO, 1958), but the grain-sizes in the Nakoso district are much smaller than those of the corresponding zones in the Gosaisyo-Takanuki district.

All the twin I have observed in metamorphic rocks of the district was on the albite law. Twinning is rather rare in the grades lower than the middle of zone B, whereas it is common in the higher grades.

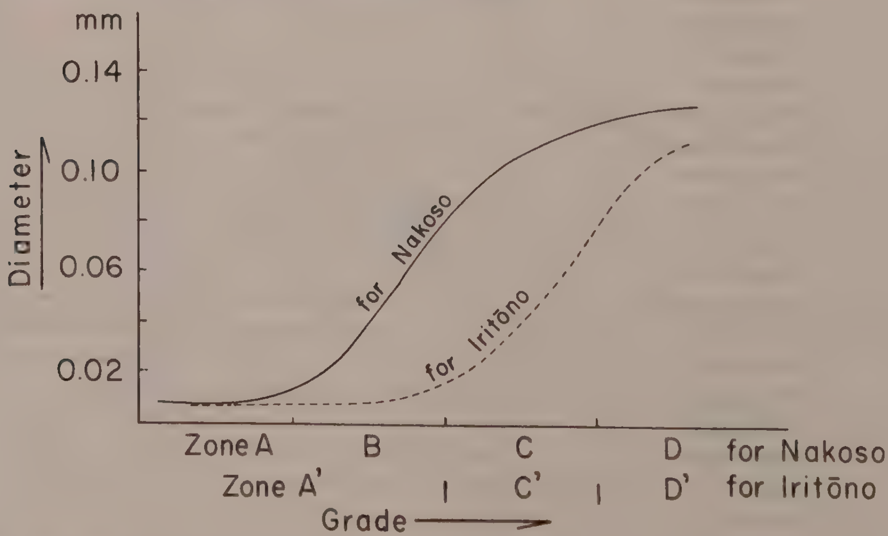

Fig. 16. Schematic diagram showing the average grain-sizes of plagioclases in ordinary basic metamorphic rocks of various zones in the Nakoso regional metamorphic terrain and in the Iritōno contact aureole. (The grain-sizes of plagioclases in psammitic rocks are generally larger than those in basic rocks of the same grades.)

Zonal structure: The zonal structure of plagioclase is very common in and characteristic of zone B, whereas it is scarcely observed in zones C and D and also in zone A.

The zonal structure of the plagioclase is commonly two-layered and much less commonly three- or more-layered. The boundary is usually very sharp with a Becke line. The inner zone is always more sodic than the outer, except where a retrogressive change is supposed. The existence of such zonal structure of plagioclase indicates that the metamorphism of the district was progressive. The lack of zonal structure in zone A is probably due to the smallness in the rate of compositional change of plagioclase with metamorphic grade, as shown in Fig. 17. On the other hand, the plagioclases of zone B are strongly zoned owing to a large rate of compositional change in this grade. The weakness of the zonal structure in zone C would be due to the increasing scope of diffusion at elevated temperatures.

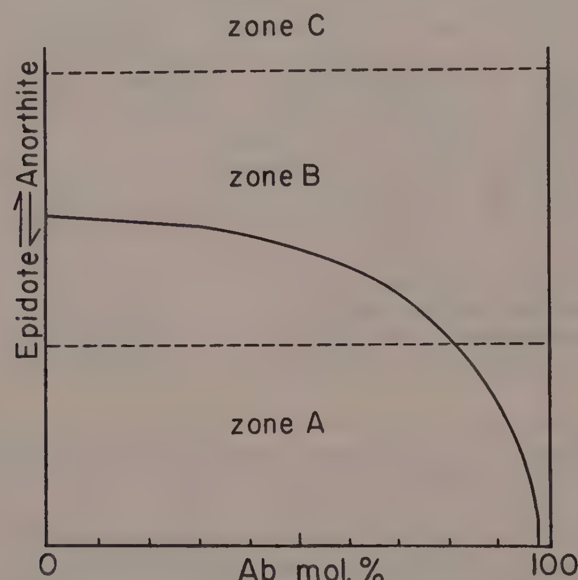

Fig. 17. Change of chemical composition of plagioclase coexisting with epidote in basic rocks with advancing metamorphism in the Nakoso district.

Composition: The compositions of plagioclases were determined from the refractive indices, measured by the immersion method. The curves of CHAYES (1952) were adopted. In zoned crystals, the determinations were made on their marginal parts, which are supposed to have been in chemical equilibrium with the coexisting minerals. According to the results, the An content of plagioclase is 3% in the typical part of zone A, 20% in the transitional part between zones A and B, and becomes rapidly more calcic with advancing metamorphism reaching labradorite at the entrance to the middle-grade part of zone B. The results are summarized in Fig. 17.

Potash Felspar

Data

Potash felspar occurs commonly in pelitic and psammitic metamorphic rocks, and rarely in calcic rocks also. In pelitic and psammitic rocks, it is generally

in a very small amount up to the higher-grade part of zone B, filling interstices between quartz and plagioclase grains, whereas it becomes fairly abundant in the higher grades. The microscopic characters of potash felspars of five thin sections were studied in detail. Three of these sections are from zone C, one from the highest-grade part of zone B and one from the middle-grade part of zone B. The results will be given below:

Specimen No. FS 54A3' (from the middle-grade part of zone B)

In general, the development of quadrille twinning is good. Generally, large crystals show zonal structure, and small ones do not. The optic angles of five grains were measured.

(1): Large grain showing zonal structure, the margin as well as the core showing clear quadrille twinning. $2V_x$ (core)=72.5° and $2V_x$ (margin)=69°.

(2): Large grain showing zonal structure without sharp boundary. $2V_x$ (core)=67° and $2V_x$ (margin)=65°.

(3): Small grain lacking in zonal structure. $2V_x$=65°.

(4): Small grain lacking in zonal structure. $2V_x$=66.5°.

(5): Small grain lacking in zonal structure. $2V_x$=64°.

Specimen No. FS 56051209 (from the higher-grade part of zone B)

Some crystals show zonal structure and the others do not. The optic angles of two grains were measured.

(1): Small grain without zonal structure. $2V_x$=53°.

(2): Large grain with zonal structure. $2V_x$ (core)=57° and $2V_x$ (margin)=53°.

Specimen No. FS 54M13 (from zone C)

Most crystals have zonal structure, the core showing commonly faint moiré appearance and the margin not. The optic angles of two large zoned crystals were measured.

(1): $2V_x$ (core)=60° and $2V_x$ (margin)=55°–56.5°.

(2): $2V_x$ (core)=65.5° and $2V_x$ (margin)=52.5°.

Specimen No. FS56051317 (from zone C)

Some grains show extremely faint moiré appearance. The optic angles of three grains were measured.

(1): Small homogeneous crystal. $2V_x$=58°.

(2): Large zoned crystal, the core showing extremely faint moiré appearance and $2V_x$= 67°, while the margin showing normal complete extinction without moiré appearance and $2V_x$=54°.

(3): Large zoned crystal, the core and the margin showing normal complete extinction without moiré appearance and $2V_x$=61.5° and $2V_x$=54.5° respectively. Fig. 18(b) is a sketch of this grain.

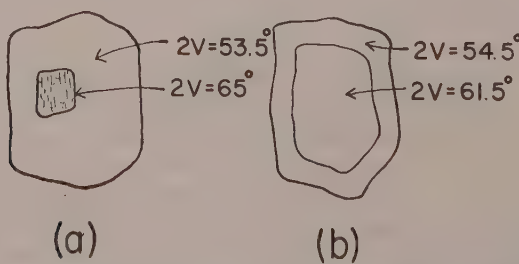

Fig. 18. (a) Sketch of the grain (*2*) of Specimen FS54D16'. The core shows quadrille twinning and the margin does not.
(b) Sketch of the grain (*3*) of Specimen FS56051317. Neither core nor margin shows any trace of twinning.

Specimen No. FS 54D16' (from zone C)

Most crystals are homogeneous and are devoid of zonal structure and quadrille twinning,

though some have a small core showing quadrille twinning. The optic angles of two crystals were measured.

(1): Large homogeneous crystal without quadrille twinning. $2V_x=54°$.

(2): Zoned large crystal, the core showing quadrille twinning and $2V_x=65°$, while the margin being devoid of the twinning and $2V_x=53.5°$. Fig. 18(a) is a sketch of this grain.

Summary of the Results

From the above observations the following remarks may be made.

(1) The optic angle is variable not only within a single specimen, but also within a single grain of the mineral. The minimum value of the optic angle in a single specimen becomes smaller with increasing grade of metamorphism: it is about 64° in the middle-grade part of zone B, and about 54°–52° in the higher-grade part of zone B as well as in zone C. The minimum value of the optic angle in one specimen probably represents the highest grade reached by the rock. The maximum value within a single specimen also tends to become smaller with increasing grade of metamorphism.

(2) The change of the optic angle with advancing metamorphism is also traceable within a single specimen. Crystals, especially large ones, often show zonal structure, the optic angle of the outer zone being always smaller than the inner. The change of the optic angle from core to margin is always gradational without a sharp boundary. Small crystals which are usually free from zonal structure have a similar optic angle as the margin of larger zoned crystals in most cases.

(3) Quadrille twinning, an indicator of triclinic symmetry, has not been observed in the crystals having the optic angles close to or less than 60°. In general, the quadrille twinning is extremely faint, if any, in zone C and it becomes clearer with decreasing grade and developes well in the middle-grade part of zone B.

Discussions and X-Ray Work

It is generally stated that common orthoclase has an optic angle in the range of about 60°–40°. Then, it may be concluded that orthoclase was the stable form of potash felspar in the higher-grade part of zone B and still higher grades. Some one, however, might consider that the measured optic angles represent the superposition effect of fine segments in quadrille twinning of microcline and that they are somewhat different from the true optic angle which would be measured on a single segment of microcline. To clarify this point, all the materials whose microscopic features are already given were examined by the X-ray powder method.

On these potash felspars, the angular separation of two reflections, 131 and $1\bar{3}1$, was observed in X-ray powder diffraction patterns. Specimens were purified by means of heavy solution and the isodynamic separator. Powder patterns were taken with a Norelco Geiger counter X-ray diffractometer using copper $K\alpha$ radiation. Portions of the powder patterns of two of them (Specimen Nos. FS56051317 and FS54A3′) are shown in Fig. 19, together with those of monoclinic adularia from Alpine vein, St. Gotthard, Switzerland, and microcline-perthite from an Isikawa pegmatite, Hukusima Prefecture, Japan, for comparison.

The 131 and $1\bar{3}1$ reflections are widely separated in the microcline of the Isikawa microcline-perthite, whereas they are united to form a single peak in the St. Gotthard adularia. The angular distance between the two reflections decreases as the symmmetry becomes closer to monoclinic one. The potash

felspars of the Nakoso district examined are intermediate between the Isikawa and St. Gotthard. The shape and height of peaks suggest that the Nakoso felspars are mixtures of materials with variable angular distances, and that the angular distance tends to decrease with increasing grade of metamorphism. It is clear from the X-ray powder patterns that some potash felspars of zone C and the higher-grade part of zone B are nearly or truely monoclinic, but it cannot be decided by this method whether any of them have true monoclinic symmetry. *The peak width decreases with increasing grade of metamorphism. It corresponds to the fact that the largest value of the optic angle within a single specimen tends to decrease with increasing grade of metamorphism.* Therefore it is considered that the adjustment of the structural state to the changing metamorphic conditions takes place not only in the marginal part but also in the central part of the potash felspar grains.

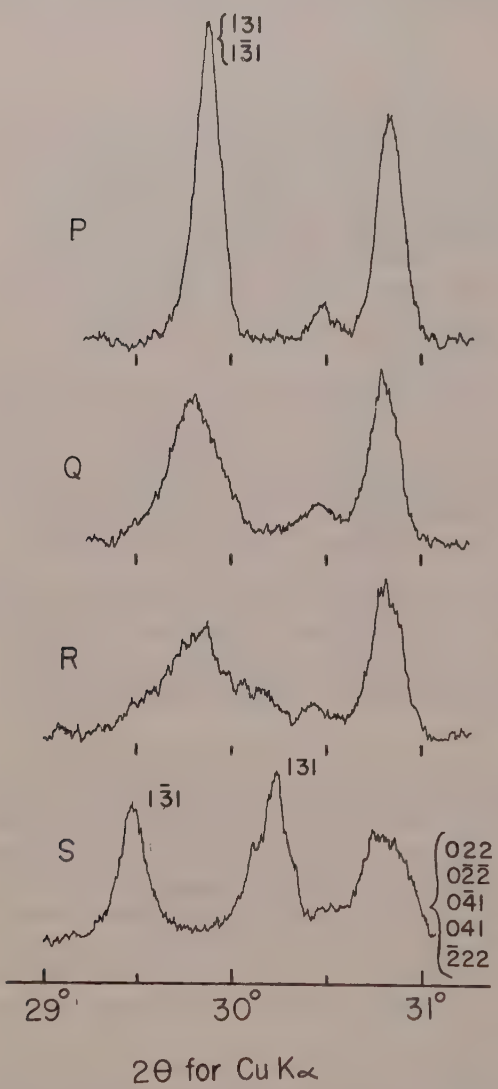

Fig. 19. 131 and 1$\bar{3}$1 reflections in powder diffraction patterns of potash felspars.
P: adularia from Alpine vein of St. Gotthard.
Q: potash felspar from zone C of the Nakoso district.
R: potash felspar from the middle-grade part of zone B of the Nakoso district.
S: microcline-perthite from pegmatite of Isikawa, Hukusima Prefecture, Japan.

Similar features may be noticed in the composite peak at 2θ=about 30.8°, which represents the reflections of (022), (041) and $\bar{2}22$. The peak becomes narrower and higher with increasing grade of metamorphism. This also manifests the decrease of triclinicity with advancing metamorphism.

Recently, K. S. HEIER (1957) has found a similar symmetry change in potash felspars from Norwegian metamorphic rocks. According to him potash felspar aquires monoclinic symmetry at a grade slightly below the boundary between the granulite and amphibolite facies. In this case also, the monoclinic potash felspar is common orthoclase.

From the diffuseness of the X-ray diffraction spots of common orthoclase, F. LAVES (1950) concluded that the mineral has no stability field. However, HEIER and I showed that orthoclase is produced by increasing as well as decreasing

metamorphisms. A more complete approach to the equilibrium would be expected in these cases than in the laboratory. Then it follows that *orthoclase has its own stability field at high grades of metamorphism.*

According to E. SPENCER (1937) and others the heat treatment of microcline makes the optic angle gradually smaller to the values of orthoclase and further to those of sanidine. In the metamorphism of the present district, the optic angle becomes smaller with increasing grade. Thus, the optic angle of potash felspar may be useful as an indicator of metamorphic grade.

As regards the Nakoso metamorphic rocks, the typical quadrille twinning that has been commonly regarded as a combination of albite and pericline twins, is present in the felspars having optic angles larger than about 60°. F. LAVES (1950) considered on the basis of crystal geometry, that such a twinning is indicative of inversion from an original monoclinic crystal, and hence he assumed that practically all potash felspars crystallized initially with monocliic symmetry. In the course of decreasing triclinicity of microcline with advancing metamorphism in the Nakoso district, the twin lamellae of the quadrille twinning becomes gradually finner. In this case, the mineral could not have had the monoclinic symmetry, and then the hypothesis of LAVES cannot be applied. *The quadrille twinning of the metamorphic microclines is considered to be intrinsic and not secondary.*

The refractive indices of potash felspars and of associated sodic plagioclases, with the compositions determined therefrom, are shown in Table 6.

Table 6. Paragenic relations between potash felspars and associated plagioclases.

Specimen No.	Potash felspar	Plagioclase
FS 56051317 (zone C)	α=1.518 γ=1.525	α=1.541 8% An
FS 54D21 (the higher-grade part of zone B)	α=1.517 γ=1.524	max. γ=1.559 44–39% An min. α=1.548
FS 54A3'' (the middle-grade part of zone B)	α=1.519 γ=1.525	max. γ=1.549 27–18% An min. α=1.537

As shown in the table, the refractive indices or the compositions of potash felspars appear to be independent of the metamorphic grade, though the refractive indices of ordinary accuracy give merely a rough estimation of the composition for alkali felspars.

The inversion of potash felspar from triclinic to monoclinic symmetry may be assumed to take place practically at a definite temperature regardless of the total pressure prevailing, because the volume change in this inversion is extremely small. Then, the symmetry change of potash felspar appears to be useful as a geologic thermometer, and thereby we can compare the temperatures of the appearance or disappearance of a certain mineral in different metamorphic terrains.

In the Pre-Cambrian metamorphic terrains of Norway, K. S. HEIER (1957) showed that the inversion of potash felspar takes place at a temperature a little below the boundary between the granulite and amphibolite facies, or at the grade where common hornblende begins to break down into orthopyroxene and clinopyroxene. On the other hand, in the Nakoso district, the same symmetry change of potash felspar takes place between the middle- and the higher-grade parts of zone B. Then, in this case, there is a fairly long grade-interval between the

symmetry change of potash felspar and the first appearance of orthopyroxene. Thus, in the former terrains the appearance of orthopyroxene resulted from the break-down of hornblende may have been at a lower temperature than in the Nakoso.

Calciferous Amphiboles

Introductory statement

Admittedly, calciferous amphibole is one of the most common constituent minerals in metamorphic rocks. Under the favourable chemical conditions, it is stable from the actinolite-greenschist facies up to the lower part of the granulite facies. Many authors have long studied the hehavior of calciferous amphiboles in metamorphism.

J. D. H. WISEMAN (1934) noticed that there are distinct differences in the character of amphibole between the epidiorites of the garnent zone and those of the chlorite and biotite zones in the Grampian Highlands of Scotland: The refractive indices of the majority of hornblendes from the garnet zone are higher than those from the chlorite and biotite zones; the total Al as well as Al^{IV} replacing Si is more abundant and the Fe^{+2}/Mg ratio is considerably higher and the CaO content is a little lower in the amphiboles of the garnet zone than in those of the chlorite and biotite zones. He described also the color change of the mineral with advancing metamorphism: the color is pale green in the chlorite and biotite zones, blue-green in the garnet zone, probably green in most of the sillimanite zone and brown in the vicinity of the older granites.

P. ESKOLA stated that the change of actinolite to common hornblende takes place in his epidote-amphibolite facies (ESKOLA, BARTH, and CORRENS, 1939). Then he suggested "Die Amphibole scheinen sehr empfindliche Indikatoren der Temperatur zu sein, und wenn sie aus verschiedenen Faziestypen genügend eingehend untersucht worden sind, wird man sie als zuverlässige geologische Thermometer anwenden können."

W. T. HARRY (1950) presented a diagram showing regular increase of Al^{IV} content in metamorphic calciferous amphiboles with increasing grade of metamorphism and he suggested that the amount of Al^{IV} in metamorphic calciferous amphiboles is a function of the temperature at which recrystallization took place.

Many authors have discussed the relation between the group of tremolite-actinolite and that of common hornblende in various ways: some authors have considered that there exists a miscibility gap between the two groups, whereas others supposed a continuous relation between the two. The former opinion was held by H. BERMAN (1937) and N. SUNDIUS (1946), whereas the latter was expressed by W. KUNITZ (1930) and S. FOSLIE (1945).

In the Nakoso district, calciferous amphiboles occur as a chief constituent from zone A, the lowest grade, up to zone D, the highest grade, in basic metamorphic rocks.

The Z-axial color of amphiboles of the ordinary basic schists changes regularily with advancing metamorphism. Thus, the color of amphibole was used as a reliable indicator to draw zone boundaries on the geologic map of the present metamorphic area.

As regards the amphiboles of zone A, I have not yet succeeded in obtaining samples pure enough for analysis, owing to their fine fibrous nature. Their optic properties indicate that they belong to the tremolite-actinolite series. As regards

hornblendes from zones B and C, five new analyses were made, and they were shown to be common hornblende very rich in Al^{IV}.

Optical properties

Z-axial color: The Z-axial color of amphiboles of zone A ranges from pale green to practically colorless; that of zone B is blue-green (i.e. from bluish green to greenish blue), and the color is much deeper than that of zone A; that of zone C is green, greenish brown or brown, the brown color without greenish tinge representing the higher-grade part of zone C; that of zone D is brown. Thus, the trend of color variation with increasing grade of metamorphism generally follows the scheme observed in the Grampian Highland epidiorites.

Optic angle and refractive indices: The optic angle and refractive indices were measured on many amphiboles from the four zones. The results were plotted on the 2V–γ diagram given in Fig. 20. As shown in the figure, points for

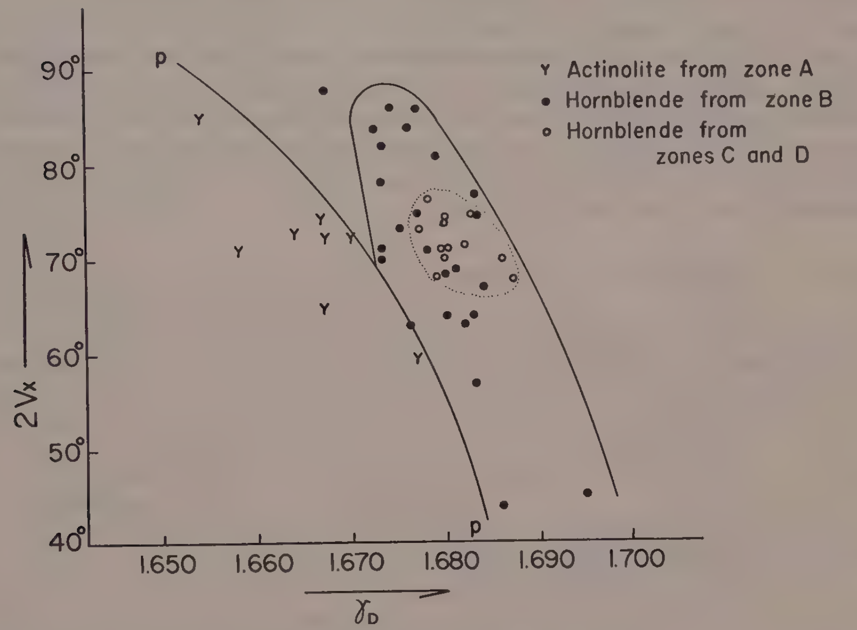

Fig. 20. 2V-γ diagram for hornblendes from metamorphic rocks of various grades in the Nakoso district.

amphiboles of zone A are distributed inside the line p–p and those for amphiboles of the higher zones outside the same line. In general, amphiboles of zones C and D occupy a fairly limited field, whereas those of zone B spread over a much wider field.

According to J. D. H. Wiseman (1934), in the chlorite and biotite zones of the Dalradian series, 90 per cent of the measured amphiboles from many different epidiorites have an index β ranging from 1.632 to 1.650, whereas only 10 per cent have an index β between 1.651 and 1.677; On the other hand, in the garnet zone, 72 per cent have an index β ranging from 1.670 to 1.685, whereas 28 per cent have an index β between 1.663 and 1.669. His observation on the refractive index of amphiboles is generally in harmony with the figure given for the Nakoso metamorphic amphiboles.

Zonal structure

The zonal structure of amphibole is commonly observed in the higher-grade part of zone A and the lower-grade part of zone B, and rarely also in the higher-grade part of zone B. The zoned crystals consist of a very pale green or practically colorless core and a blue-green periphery. The core has a larger optic angle, lower refractive indices and a higher birefringence than the periphery. The optic properties of the pale core agree with those of the actinolite of zone A and those of the periphery agree with those of the blue-green hornblende of zone B. The boundary between the actinolite of the core and the blue-green hornblende of the periphery is very sharp. A Becke line was noticed when the boundary surface was oriented nearly parallel to the axis of the microscope by means of the universal stage.

Amphiboles of zone A and of the transitional part between zones A and B are often in parallel growth of fine fibers of actinolite and blue-green hornblende. Because of the fineness, this can hardly be noticed in thin sections. Some specimens were finely crushed and immersed in an oil with a refractive index close to that of the amphibole. Observations of these samples with the high-power objective sometimes showed clearly that fibers of actinolite and of blue-green hornblende are in parallel growth with a Becke line between them and either of the two amphiboles does not enclose the other. These features suggest the existence of a miscibility gap between them under the metamorphic conditions concerned.

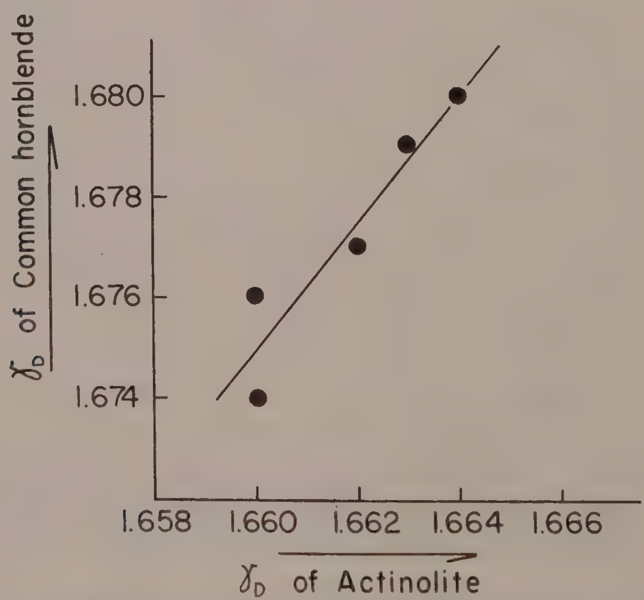

Fig. 21. Relation between the refractive indices of blue-green common hornblendes and associated actinolites in the higher-grade part of zone A and the lowest-grade part of zone B in the Nakoso district.

The index γ were carefully measured on several coexisting pairs of the two amphiboles from zone A and the lowest-grade part of zone B. The results are given in Fig. 21. As shown in the figure, the index of the actinolites and that

of the coexisting blue-green hornblendes are in a definite relationship. This suggests that the two amphiboles were probably in equilibrium with each other in these metamorphic grades.

Chemical analyses

Among the five analysed hornblendes, two are from zone C and the rest are from zone B. Their host rocks were finely crushed and then hornblende was concentrated by the isodynamic separator and purified by means of Clerici solution. The purification of these samples were practically complete, except in the lowest-grade hornblende (No. 10).

The analyses together with their physical data are set out in Table 7, along with five other analyses of hornblendes from metamorphic rocks of the Gosaisyo-Takanuki district (A. MIYASHIRO, 1958). Their atomic ratios were calculated on the anhydrous basis of O=23, as given in Table 8.

The analysed sample No. 10 includes small amounts of plagioclase and hematite. The plagioclase was estimated to be less than 5 per cent by weight and the amount of the hematite was found to correspond roughly to the total amount of Fe_2O_3 in the analysis. Then, the analysis was corrected by subtracting 5 per cent of plagioclase (An_{35}) and all the Fe_2O_3 content of the analysis. In Table 9 the atomic ratios on the anhydrous basis of O=23, calculated from the original analysis and from the corrected value are shown in columns A and B respectively. The difference is small.

Brief descriptions of the host rocks of the analysed hornblendes are given below;

No. 1: *Clinopyroxene-bearing amphibolite* (Specimen No. FS 54D14') from Yamatama, Ogawa-mati, Nokoso City, Hukusima Prefecture.

This rock was collected at a locality about 25 m. away from the contact with the gabbro and this rock probably belongs to the highest-grade part of zone C or the transitional grade between zones C and D. It is mainly composed of brown hornblende and plagioclase (labradorite), with a subordinate amount of clinopyroxene. As accessory constituents, sulphide mineral and apatite occur.

No. 2: *Clinopyroxene-bearing amphibolite* (Specimen No. FS 54 C 9) from Yōzikata, Sekimoto-mura, Taga-gun, Ibaragi Prefecture.

As regards the metamorphic grade, this rock probably belongs to the higher-grade part of zone C. It is mainly composed of brown hornblende, plagioclase (labradorite) and clinopyroxene with small amounts of sphene, quartz and opaque mineral.

No. 3: *Amphibolite* from Yokogawa, Hurudono-mura, Higasi-sirakawa-gun, Hukusima Prefecture (TSUBOI, 1935).

As regards the metamorphic grade this rock belongs to zone C.

No. 4: *Biotite-amphibolite* (Specimen No. AM 470808–3) from Kamata, Hurudono-mura, Higasi-sirakawa-gun, Hukusima Prefecture (MIYASHIRO, 1958).

This rock probably belongs to the higher-grade part of zone C. It is composed of hornblende and plagioclase (An_{20-25}) with a smaller amount of biotite. Very small amounts of opaque mineral, apatite and sphene are also present.

No. 5: *Clinopyroxene-amphibolite* (Specimen No. AM 470803–11) from between Ōtake and Tinokubo, Hurudono-mura, Higasi-sirakawa-gun, Hukusima Prefectrue (MIYASHIRO, 1958).

This rock belongs to zone C (probably its lower-grade part). It is mainly composed of hornblende, plagioclase (core An_{55}, rim An_{75}) and clinopyroxene with small amounts of opaque mineral, sphene and apatite.

No. 6: *Clinopyroxene-rich lens in amphibolite* (Specimen No. AM 470803–12) from Domeki, Hurudono-mura, Higasi-sirakawa-gun, Hukusima Prefecture. (MIYASHIRO, 1953a).

Table 7. Chemical analyses of hornblendes from the Nakoso and Gosaisyo-Takanuki districts.

	Zone C					Zone B				
	1	2	3	4	5	6	7	8	9	10
SiO_2	42.94	45.62	42.44	43.20	44.36	40.96	44.03	42.62	44.07	44.60
Al_2O_3	12.56	8.87	12.50	12.44	11.69	11.70	12.33	12.75	12.37	12.12
TiO_2	1.89	1.13	3.09	1.65	1.26	0.99	0.46	0.53	1.70	0.87
Fe_2O_3	1.83	2.85	2.07	3.21	1.29	5.32	3.33	6.01	0.18	2.72
FeO	13.42	16.09	12.38	10.10	16.63	13.30	13.27	14.00	10.23	16.21
MgO	10.84	10.13	11.43	13.27	9.71	11.06	12.17	8.52	14.20	8.89
MnO	0.29	0.32	0.30	0.21	0.43	0.69	0.41	0.33	0.18	0.37
CaO	11.31	11.42	10.90	11.36	11.82	12.72	10.82	11.65	12.42	10.78
Na_2O	1.99	1.27	2.21	2.72	0.79	1.06	1.59	1.28	1.00	0.98
K_2O	0.35	0.33	0.14	0.40	0.50	1.27	0.23	0.55	0.30	0.50
$H_2O(+)$	2.23	1.92	1.94	1.38	1.67	1.50	1.32	1.91	2.85	2.03
$H_2O(-)$	0.22	0.16	0.15	0.07	0.12	0.06	0.07	0.12	0.03	0.11
F	n.d.	n.d.	n.d.	n.d.	n.d.	0.13	n.d.	n.d.	n.d.	n.d.
P_2O_5	n.d.	n.d.	0.23	0.07	0.12	n.d.	0.07	n.d.	n.d.	0.21
Total	99.87	100.11	99.78	100.08	100.39	100.76	100.10	100.27	99.53	100.39
α_D	1.659	1.662	1.653	1.654	1.650	1.663	1.657	1.665	1.656	1.660
γ_D	1.688	1.687	1.676	1.680	1.679	1.686	1.675	1.683	1.673	1.682
$2V_X$	76°	68.5°	84°	83°	79°	44°	74°	65.5°	82°	63°
$c \wedge Z$	26°	23°	15°	19°	15°	25°	18°	20°	19°	15°
X	p. brown	p. yellow	p. yellow	v. p. yellow	v. p. yellow	yellow	v. p. yellow	p. yellow	v. p. yellow	colorless
Y	brown	greenish brown	sepia-brown	green-yellowish brown	yellow-greenish brown	d. yellowish green	l. green	green	p. yellow-brownish green	l. green
Z	brown	greenish brown	sepia-brown	greenish brown	yellow brownish green	bluish green	l. bluish green	greenish blue	bluish green	l. bluish green

Note: In No. 2 β=1.674; In No. 1 Sp. gr.=3.164. p.=pale, v.p.=very pale, l.=light, d=deep.

This rock belongs to the highest-grade part of zone B. The clinopyroxene-rich lense in amphibolite is composed mainly of clinopyroxene (Di_{60} Hd_{40}) and subordinately of bluish green hornblende, plagioclase (andesine), epidote, sphene and opaque mineral. Surrounding amphibolite is composed mainly of bluish green hornblende and subordinately of clinopyroxene, plagioclase (andesine) and sphene.

No. 7: *Biotite-bearing hornblende schist* (Specimen No. FS 54A4) from Yōzikata, Sekimoto-mura, Taga-gun, Ibaragi Prefecture.

This rock belongs to the middle-grade part of zone B. It is composed mainly of bluish green hornblende and plagioclase (andesine), with small amounts of biotite and opaque mineral.

No. 8: *Biotite-hornblende schist* (Specimen No. FS 54A7) from Yōzikata, Sekimoto-mura, Taga-gun, Ibaraki Prefecture.

This rock was obtained from 200 m. away from the locality of No. 9, and belongs to the middle-grade part of zone B (a slightly lower grade than No. 9). It is composed mainly of blue-green hornblende, biotite and plagioclase (andesine) with a small amount of opaque mineral. This rock is intercalated with the quartzose bands (less than 2.0 mm. thick), but is free from quartz except in the immediate vicinity of the bands. Then, probably most of the analysed sample was not in equilibrium with quartz. Hornblende occurs generally in prismatic medium-grained crystals, but porphyroblastic stout crystals are present in some layers, less than 0.5 cm. thick. All these hornblendes are the same in their optical properties.

No. 9: *Epidote-hornblende-plagioclase-schist* (Specimen No. AM 470621–16) from Kamiyama, Tabito-mura, Iwaki-gun, Hukusima Prefecture. (MIYASHIRO, 1953a)

This rock belongs to the middle-grade part of zone B. It is composed mainly of hornblende and plagioclase (core An_{31}, rim An_{65}) with small amounts of epidote (retrogressive ?) and opaque mineral.

No. 10: *Biotite-bearing hornblende-schist* (Specimen No. AM 55090819) from Ōdaira, Tōno-mati, Iwaki-gun, Hukusima Prefecture.

It belongs to the lowest-grade part of zone B. It is composed mainly of pale bluish green hornblende and subordinately of biotite and plagioclase (andesine) with much smaller amounts of hematite and actinolitic amphibole. The hornblende occurs in fine lath-shaped long prisms with marked parallel arrangement. This rock is very fine-grained and hence the absence of quartz was ascertained by the X-ray powder method. The analysed sample of this hornblende was not pure as mentioned before (see Table 9).

Table 8. Atomic ratios on the anhydrous basis of O=23.

	Zone C					Zone B			
	1	2	3	4	5	6	7	8	9
Si	6.377	6.800	6.277	6.291	6.573	6.128	6.443	6.361	6.453
Al^{IV}	1.623	1.200	1.723	1.709	1.427	1.872	1.557	1.639	1.547
Al^{VI}	0.575	0.358	0.455	0.425	0.615	0.191	0.570	0.604	0.588
Fe^{+3}	0.205	0.320	0.231	0.352	0.144	0.598	0.367	0.674	0.019
Ti	0.211	0.126	0.344	0.181	0.141	0.111	0.051	0.059	0.187
Fe^{+2}	1.666	2.005	1.531	1.230	2.060	1.663	1.623	1.747	1.252
Mg	2.398	2.249	2.519	2.878	2.143	2.465	2.653	1.894	3.097
Mn	0.037	0.040	0.037	0.026	0.054	0.087	0.051	0.042	0.022
Ca	1.799	1.823	1.727	1.772	1.876	2.038	1.695	1.862	1.948
Na	0.573	0.367	0.634	0.768	0.226	0.307	0.452	0.371	0.283
K	0.066	0.063	0.027	0.070	0.094	0.243	0.042	0.104	0.056

Note: P_2O_5 is neglected from the calculation.

Table 9. The atomic ratios of hornblende No. 10 as compared with the ratio corrected for the impurities.

Molecular Proportion	A	B	Atomic Ratio	A	B
SiO_2	7426	6931	Si	6.622	6.709
Al_2O_3	1189	1062	Al^{IV}	1.378	1.291
TiO_2	109	109	Al^{VI}	0.742	0.765
Fe_2O_3	170	0	Fe^{+3}	0.303	0.000
FeO	2256	2256	Ti	0.097	0.106
MgO	2205	2205	Fe^{+2}	2.012	2.184
MnO	52	52	Mg	1.966	2.134
CaO	1922	1856	Mn	0.046	0.050
Na_2O	158	97	Ca	1.714	1.797
K_2O	53	53	Na	0.282	0.188
			K	0.094	0.103

Isomorphous substitutions and molecular Compositions

A. F. HALLIMOND (1943) and N. SUNDIUS (1946) demonstrated that the aparently complicated composition relations in the calciferous amphiboles can be expressed by a fairly small number of molecules. They have successfully derived the formulas of various members from the tremolite formula by applying the following types of substitution: $Na^{XII}\cdot Na^{VIII}$ for Ca, $Na^{XII}\cdot Al^{IV}$ for Si, $Na^{VIII}\cdot Al^{VI}$ for Ca·Mg and $Al^{VI}\cdot Al^{IV}$ for Mg·Si, which will be called sodatremolite, edenite, glaucophane and tschermakite substitutions respectively in this paper.

I have noticed that for a closer examination of the compositions of calciferous amphiboles, a few more types of substitution must be taken into considerations. Usually some amount of Ti is present in common hornblendes. Judging from the ionic radius, most of Ti ions are probably in 6-coordinated positions. If we start from the tremolite formula, Ti in the amphiboles would be interpreted as is introduced by the substitution of $Ti^{VI}\cdot Al_2^{IV}$ for $Mg\cdot Si_2$, which will be called the titanoamphibole substitution.

In the atomic ratios calculated on the anhydrous basis of O=23, the total number of Mg, Fe^{+2}, Mn, Fe^{+3}, Al^{VI} and Ti is usually larger than 5, but the 6-coordinated positions can accomodate only 5 atoms. Then the excess over 5 must be in 8-coordinated positions together with Ca and/or Na. Probably larger atoms, Mn, Fe^{+2} and Mg enter the 8-coordinated positions more readily, and they make cummingtonite molecule. This substitution will be called cummingtonite substitution.

In some common hornblendes, the total number of Mg, Fe^{+2} and Mn in 8-coordinated positions and of Ca is over 2 and then a part of the Ca must be in the so-called 'A' sites of the structure. The entrance of the divalent ion Ca into the 'A' sites is probably accompanied by the replacement of Si by the trivalent ion Al to maintain electrical neutrality. This substitution, $Si_2 \longleftarrow Ca^{XIII}\cdot Al_2^{IV}$ will be called calcium-edenite substitution.

All these types of substitution applied to the tremolite formula $Ca_2Mg_5Si_8O_{22}(OH)_2$, cover practically the whole chemical field of the amphiboles, provided that the Fe^{+2}–Mg and Al–Fe^{+3} substitutions are neglected. They are synoptically shown below:

Table 10. End members resulting from the various types of substitution and corresponding ordinary molecules.

	End members					Ordinary molecules					
Denotation	Structural positions A	W	X+Y	Z		Name	Structural positions A	W	X+Y	Z	
Tiam		Ca_2	Mg_1Ti_4	Al_8	$O_{22}(OH)_2$	Titanoamphibole		Ca_2	Mg_1Ti_4	Al_8	$O_{22}(OH)_2$
Cum		Mg_2	Mg_5	Si_8	$O_{22}(OH)_2$	Cummingtonite		Mg_2	Mg_5	Si_8	$O_{22}(OH)_2$
Ce′	Ca_4	Ca_2	Mg_5	Al_8	$O_{22}(OH)_2$	Calcium-edenite	Ca	Ca_2	Mg_5	Al_2Si_6	$O_{22}(OH)_2$
St′	Na_2	Na_2	Mg_5	Si_8	$O_{22}(OH)_2$	Sodatremolite	Na	NaCa	Mg_5	Si_8	$O_{22}(OH)_2$
Ed′	Na_8	Ca_2	Mg_5	Al_8	$O_{22}(OH)_2$	Edenite	Na	Ca_2	Mg_5	Al_1Si_7	$O_{22}(OH)_2$
Gl		Na_2	Mg_3Al_2	Si_8	$O_{22}(OH)_2$	Glaucophane		Na_2	Mg_3Al_2	Si_8	$O_{22}(OH)_2$
Ts′		Ca_2	Al_5	Al_5Si_3	$O_{22}(OH)_2$	Tschermakite		Ca_2	Mg_3Al_2	Al_2Si_6	$O_{22}(OH)_2$
Tr		Ca_2	Mg_5	Si_8	$O_{22}(OH)_2$	Tremolite		Ca_2	Mg_5	Si_8	$O_{22}(OH)_2$

Titanoamphibole substitution	$Ti \cdot Al_2 \longrightarrow Mg \cdot Si_2$
Cummingtonite substitution	$Mg \longrightarrow Ca$
Calcium-edenite substitution	$Ca \cdot Al_2 \longrightarrow Si_2$
Sodatremolite substitution	$Na_2 \longrightarrow Ca$
Edenite substitution	$Na \cdot Al \longrightarrow Si$
Glaucophane substitution	$Na \cdot Al \longrightarrow Ca \cdot Mg$
Tschermakite substitution	$Al_2 \longrightarrow Mg \cdot Si$

These substitutions lead to the end members shown in Table 10. Some of these molecules do not fulfill the requirement of the amphibole structure (Na+Ca in the 'A' sites$<$1), and hence do not occur in nature for themselves. They become real only as a molecule in the amphibole solid solutions. For example, one part of Ed' and 7 parts of tremolite molecule are mixed to form edenite. Similarly, Ce′, St′ and Ts′ molecules combined with appropriate amounts of tremolite molecule form calcium-edenite, sodatremolite and tschermakite respectively. In this paper, the imaginary end members (Ed′, Ce′, St′ and Ts′) will be used in the calculation of the constituent molecules from chemical analyses. In the discussions, the corresponding ordinary molecules that are produced by combining the imaginary end members with tremolite molecule (i. e., edenite, calcium-edenite, sodatremolite and tschermakite) are used in most cases. Attention should be paid not to confuse the two kinds of molecules.

To express the chemical compositions of common hornblendes by these molecules has some advantage for comparison. Unfortunately, however, the contents of these molecules in a common hornblende depend to some extent on the order of calculation of the molecules. Then, a definite rule for the order is necessary to make the results consistent.

The *preferred procedure of calculation of the molecules* is as follows*:

(1) The atomic numbers are calculated from the analysis on the anhydrous basis of O=23.

(2) The atomic numbers are grouped together as follows: $(Fe^{+3}+Al) \longrightarrow Al$, $(Fe^{+2}+Mg+Mn) \longrightarrow Mg$, $(Na+K) \longrightarrow Na$. Then, all the atomic numbers are arranged in the order of Si, Al, Ti, Mg, Ca and Na. These atoms are allotted first to 4-coordinated positions (Z), then to 6-coordinated positions (Y, X) and lastly to 8-coordinated positions (W) in the above order. The remainining atoms are allotted to 12-coordinated positions (A).

(3) Calculate each molecule in the order of (Tiam, Cum, Ce′), St′, (Ed′, Gl), Ts′ and Tr. The order of calculation of the molecules in a set of parentheses does not affect the results.

For example, the hornblende No. 1 was calculated as shown in Table 11. The results of the calculation of all the analyzed amphiboles on this method are shown in Table 12.

After this method of calculation, glaucophane molecule is not present in these Abukuma metamorphic hornblendes, whereas it is present in some common hornblendes from the Dalradian series.

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* The order of calculation of the molecules in hornblende is optional. The order given here has been preferred for the reason that the variations in the kinds and amounts of molecules obtained by this order with the types and grades of metamorphism are somewhat sympathetic with those of the amphiboles having the same mineral names. The kinds and amounts of molecules obtained by this order will be explained in this paper and those obtained by other orders should be able to be explained as well. Note that the Fe^{+3} contents of these hornblendes are much smaller than the Al^{+3} contents.

Table 11. Calculation of the hornblende No. 1.

	Atomic ratio		Tiam	Cum	Ce′	St′	Ed′	Gl	Ts′	Tr	Remains
Z	Si	6.377	—	0.368	—	0.436	—	—	0.468	5.104	0.001
	Al	1.623	0.422	—	—	—	0.421	—	0.780	—	—
Y	(Al, Fe^{+3})	0.780	—	—	—	—	—	—	0.780	—	—
	Ti	0.211	0.211	—	—	—	—	—	—	—	—
X	(Fe^{+2}, Mg, Mn)	4.009	0.053	0.230	—	0.273	0.263	—	—	3.190	—
W	(Fe^{+2}, Mg, Mn)	0.092	—	0.092	—	—	—	—	—	—	—
	Ca	1.799	0.106	—	—	—	0.105	—	0.312	1.276	—
	Na	0.109	—	—	—	0.109	—	—	—	—	—
A	(Na, K)	0.530	—	—	—	0.109	0.421	—	—	—	—

Table 12. Molecular proportions of the analysed hornblende from the central Abukuma regional metamorphic rocks.

	⟸ Metamorphic grade									
	Zone C					Zone B				
	1	2	3	4	5	6	7	8	9	10
Tiam	0.422	0.252	0.688	0.362	0.282	0.222	0.102	0.118	0.374	0.212
Cum	0.368	0.392	0.468	0.368	0.628	0.460	1.260	0.080	0.660	0.956
Ts′	1.248	1.185	1.098	1.243	1.214	1.262	1.499	2.045	0.971	1.224
Ce′	—	—	—	—	0.066	0.306	0.020	—	0.226	0.072
St′	0.436	0.316	0.624	0.544	—	—	—	0.472	—	—
Ed′	0.421	0.272	0.349	0.566	0.320	0.550	0.494	0.239	0.339	0.291
Tr	5.104	5.684	4.776	4.912	5.484	5.192	4.620	5.044	5.424	5.244

Note: The total of all the molecules in each hornblende is taken to be very close to 8.

Increase of the alkali content with metamorphic grade

As is shown in Table 12, the St′ molecule is generally much more abundant in hornblendes of zone C than in those of zone B, whereas the content of Ed′ molecule tends to increase only slightly. Thus, the alkali contents are generally much higher in hornblendes of zone C than in those of zone B.

In Fig. 22, the alkali contents of the hornblendes are plotted against the metamorphic grade estimated from the locality on an assumption that the grade varies regulary with the shift in the direction normal to the isograds. The hornblendes Nos. 4, 7, and 8 may be considered to have paractically the highest alkali contents possible for the metamorphic grades of their host rocks. This is related mainly to the degree of silica-saturation of their host rocks and the compositions of the associated plagioclase as explained below.

In the ordinary rocks of present metamorphic terrain, alkalies enter into hornblendes probably through the following reactions:

$$\underset{\text{Tremolite}}{Ca_2Mg_5Si_8O_{22}(OH)_2} + \underset{\text{Albite}}{NaAlSi_3O_8} \rightleftarrows \underset{\text{Edenite}}{NaCa_2Mg_5AlSi_7O_{22}(OH)_2} + \underset{\text{Quartz}}{4SiO_2} \quad ..(1)$$

$$\underset{\text{Tremolite}}{Ca_2Mg_5Si_8O_{22}(OH)_2} + \underset{\text{Albite}}{2NaAlSi_3O_8}$$

$$\rightleftarrows \underset{\text{Sodatremolite}}{Na_2CaMg_5Si_8O_{22}(OH)_2} + \underset{\text{Anorthite}}{CaAl_2Si_2O_8} + \underset{\text{Quartz}}{4SiO_2} \quad \ldots\ldots(2)$$

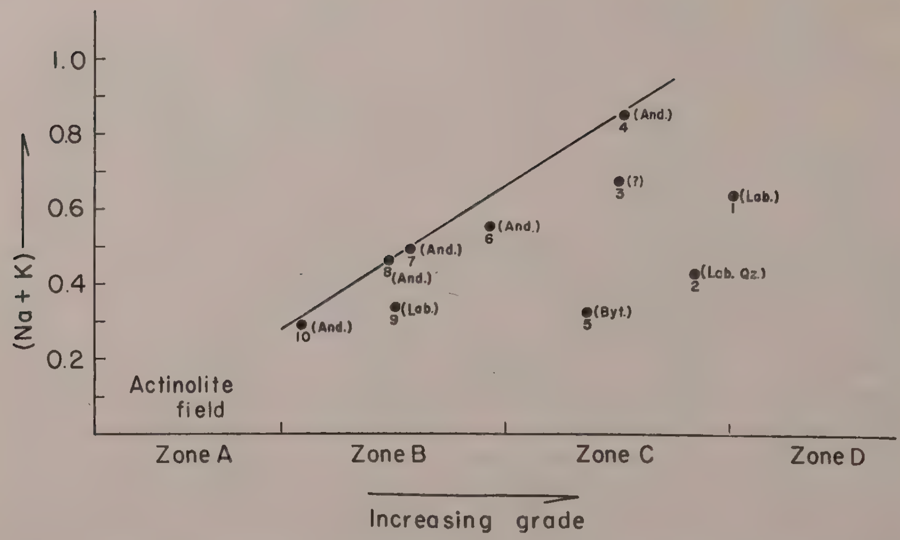

Fig. 22. Relationship between the (Na+K) contents of common hornblendes on the anhydrous basis of O=23 and the metamorphic grades for the central Abukuma regional metamorphic terrain.

And., Lab., and Byt. within parentheses represent that the coexisting plagioclase is andesine, labradorite and bytownite respectively. Qz represents that the hornblende is in equilibrium with quartz; "?" represents that the associated minerals are unknown because the host rock was not described.

In these equations, the left-hand side represents lower temperatures than the right-hand side. Silica is liberated by these reactions. In some rocks without free silica, the liberated silica may react with associated mineral or minerals. In such rocks, the reaction temperatures for these equations should become lower. Then, probably, hornblendes in rocks undersaturated with silica tend to have higher contents of edenite and sodatremolite molecules than those in the associated oversaturated rocks. A larger amount of albite molecule will be captured in the hornblende as the associated plagioclase becomes more sodic.

Tschermakite and tremolite molecules may be formed in this metamorphism through the following reactions:

$$\underset{\text{Epidote}}{6Ca_2Al_3Si_3O_{12}(OH)}+\underset{\text{Chlorite}}{Mg_5Al_2Si_3O_{10}(OH)_8}+\underset{\text{Quartz}}{7SiO_2}$$
$$\rightleftarrows \underset{\text{Tremolite}}{Ca_2Mg_5Si_8O_{22}(OH)_2}+\underset{\text{Anorthite}}{10CaAl_2Si_2O_8}+\underset{\text{Water}}{6H_2O} \quad \ldots\ldots\ldots(4)$$

$$\underset{\text{Tremolite}}{Ca_2Mg_5Si_8O_{22}(OH)_2}+\underset{\text{Chlorite}}{14Mg_5Al_2Si_3O_{10}(OH)_8}+\underset{\text{Epidote}}{24Ca_2Al_3Si_3O_{12}(OH)}+\underset{\text{Quartz}}{28SiO_2}$$
$$\rightleftarrows \underset{\text{Tschermakite}}{25Ca_2Mg_3Al_4Si_6O_{22}(OH)_2}+\underset{\text{Water}}{44H_2O} \quad \ldots\ldots\ldots(5)$$

In these equations, the left-hand side represents lower temperaures than the right-hand side. The reactions (4) and (5) which involve epidote and chlorite can be applied up to the middle of zone B where these minerals practically disappears from all the basic rocks. These reactions produce the tremolite and tschermakite molecules, thus resulting in relative decrease of the alkali-bearing molecules. The reactions require the supply of silica (either quartz or silica liberated by the accompanied reactions). Such reactions should take place at

lower temperatures in rocks with quartz than in rocks with undersaturated minerals.

Then, *hornblendes in the rocks free from quartz are expected to have generally larger alkali contents than hornblendes in the quartz-bearing rocks in the same grade.* The host rocks of the analysed hornblendes, Nos. 4, 7 and 10 are free from quartz and that of No. 8 is considered not to be in equilibrium with quartz as stated before. All these rocks are similar to olivine basalt in chemical composition, and now have the assemblage hornblende-plagioclase-biotite. The associated plagioclases are andesine, and is more sodic than the plagioclases associated with any other analysed hornblendes. Just as was expected, the hornblendes Nos. 4, 7 and 8 have the highest alkali contents for the metamorphic grade of their host rocks.

It is noteworthy that *the maximum alkali content for each grade increases with increasing grade of metamorphism.* The alkali content is low in the hornblende No. 10 from the lowest-grade part of zone B, higher in the hornblendes Nos. 8 and 7 from the middle of zone B and the highest in the hornblende No. 4 from zone C. In zones B, C and D, *the increase of the alkali content with increasing grade may be attributed to the increase of sodatremolite and edenite molecules* as is shown in Table 12.

The increase of edenite and sodatremolite molecules with increasing grade of metamorphism is in harmony with crystallo-chemical considerations. With rising temperature, the 'A' sites of tremolite are increasingly occupied by alkali atoms of the sodatremolite and edenite molecules. J. Zussman (1955) and E. J. Whittaker (1949) emphasized that the 'A' site is so large for Na ion that the binding force must be nearly of the van der Waals type rather than ionic. Na atoms in the 'A' sites would be free to wander over larger spaces and then have larger entropy than in the felspar structure. It follows that the introduction of Na atoms into the 'A' sites probably increases the entropy of the system. Then, it is reasonable that the alkali content of hornblendes tends to increase with increasing grade.

The increase of the alkali content with increasing grade is in harmony with Hallimond's figure (1943, Fig. 3) which shows statistically that the alkali content of hornblende increases from amphibolite to basalt and from oversaturated rocks to undersaturated ones.

Frequent occurrence of cummingtonite in high-grade basic metamorphic rocks

Cummingtonite is common in basic rocks of zones C and D, whereas it is very rare in those of zone B. (It is absent in zone A.) These cummingtonites coexist usually with common hornblende and plagioclase. Cummingtonite may be regarded to have been produced as a result of compositional changes of common hornblende.

As shown in Table 12, some hornblendes of zone B are very rich in cummingtonite molecules, whereas all the hornblendes of zone C are poor in the molecule. Then, the maximum content of cummingtonite molecule appears to decrease with increasing grade of metamorphism. The molecule must have been expelled to form the separate phase cummingtonite.

Cummingtonite may be produced also by the decomposition of tschermakite molecule as represented by the following equation:

$$\underset{\text{Tschermakite}}{7Ca_2Mg_3Al_4Si_6O_{22}(OH)_2}+\underset{\text{Quartz}}{10SiO_2} \rightleftarrows \underset{\text{Anorthite}}{14CaAl_2Si_2O_8}+\underset{\text{Cummingtonite}}{3Mg_7Si_8O_{22}(OH)_2}+\underset{\text{Water}}{4H_2O} \qquad \ldots\ldots\ldots\ldots(6)$$

This equation shows that the decomposition of tschermakite molecule into cummingtonite and plagioclase should take place more readily in hornblendes associated with free silica than in those not associated with free silica.

This effect of the degree of silica-saturation upon the decomposition of tschermakite molecule is clearly shown in Fig. 23. In the figure, the increase of

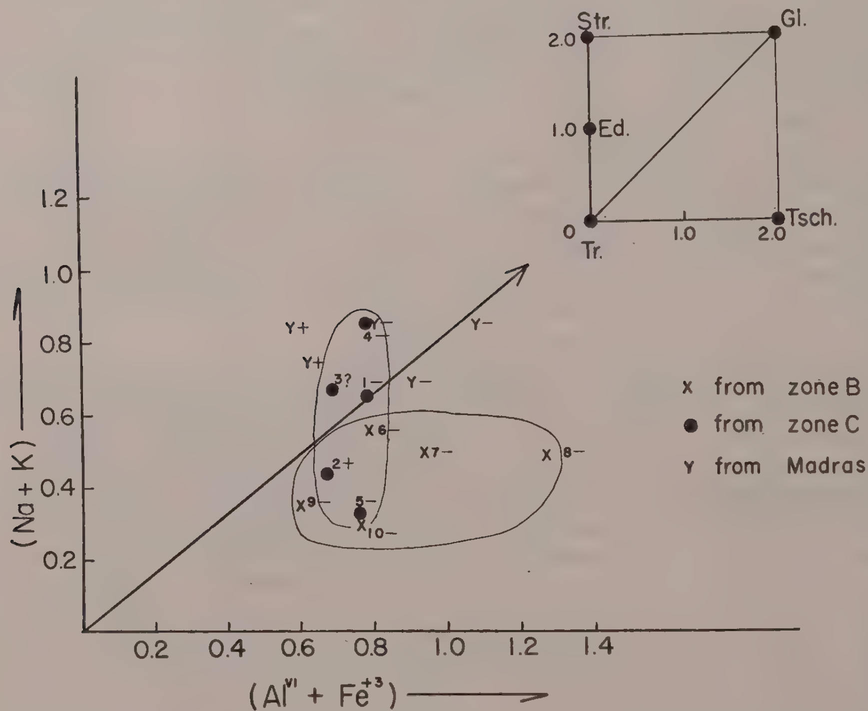

Fig. 23. Compositional variation of common hornblende with metamorphic grade and the degree of silica saturation of the host rock in the central Abukuma regional metamorphic terrain and in the charnockite area of Madras, India. The point shifts toward the right with increasing contents of tschermakite molecule, whereas it shifts upwards with increasing contents of edenite and sodatremolite molecules.
+: hornblende associated with quartz.
−: hornblende not associated with quartz.
? : hornblende with no description of its host rock.

tschermakite molecule is represented by the shift toward the right, and the increase of edenite and sodatremolite molecules by the shift upwards. Among the hornblendes of zone C, No. 2 is from a quartz-bearing schist and it falls to the left of Nos. 1, 4 and 5 which are from quartz-free schists. (The mode of the hornblende No. 3 is unknown.)

The significance of the degree of silica-saturation on the decomposition of tschermakite molecule is confirmed by the data of R. A. HOWIE (1954–55). He analysed five hornblendes from charnockites of Madras, India. They are plotted on Fig. 23 together with the hornblendes from the present district. Two of these Madras hornblendes that are associated with quartz have decidedly smaller contents of tschermakite molecules than the other three that are not associated with quartz. This will be explained by the following reaction.

$$\underset{\text{Tschermakite}}{Ca_2Mg_3Al_4Si_6O_{22}(OH)_2}+\underset{\text{Quartz}}{SiO_2} \rightleftarrows \underset{\text{Orthopyroxene}}{3MgSiO_3}+\underset{\text{Anorthite}}{2CaAl_2Si_2O_8}+\underset{\text{Water}}{H_2O} \quad \ldots\ldots\ldots (7)$$

Accordingly, the content of tschermakite molecule in hornblende associated with quartz would vary with the physical conditions of its formation.

Unfortunately, no hornblende was analysed from quartz-bearing rocks of zone B. However, analysed hornblendes of zone C tend to fall in a field which lies far to the left of No. 8 in Fig. 23. This fact suggests that tschermakite molecule tends to be expelled from hornblendes to produce the mineral cummingtonite in passage from zone B to C.

The decrease of tschermakite molecule in hornblende with increasing grade in this case is in harmony with crystallochemical considerations. As is well known, Al tends to assume 4-coordination in the crystals formed at elevated temperatures, whereas it tends to assume 6-coordination in the crystals formed at low temperatures. Tschermakite molecule carrys an Al atom in 6-coordination. This molecule decomposes with rising temperature and the liberated Al enters into plagioclase in which it is in 4-coordinated positions.

Other compositional changes with metamorphic grade

The contents of Al^{IV} of these hornblendes from zones B and C ranges from 1.200 to 1.872. The hornblende from the lowest-grade part of zone B was found to be an ordinary aluminous common hornblende, having at least 1.291 of Al^{IV}. *The contents of Al^{IV} have no systematic relation to the grade of metamorphism.* The average value of Al^{IV} of the hornblendes of zone C is slightly lower than that of zone B. Thus, HARRY's (1950) statement that the content of Al^{IV} increases regularly with metamorphic grade does not hold good. He did not distinguish between the Al^{IV} introduced by the edenite substitution and that introduced by the tschermakite substitution. The former tends to increase and the latter tends to decrease with rising temperature in high-grade metamorphism.

The Ti content of hornblendes of zone B, except No. 9, ranges from 0.059 to 0.111, whereas that of hornblendes of zone C ranges from 0.126 to 0.344. Thus, Ti is much more abundant in hornblendes of zone C than in those of zone B.

The Fe^{+3} content of hornblendes of zone C is much smaller than that of hornblendes of zone B, except No. 9. As stated by A. MIYASHIRO (1958), the $Fe^{+3}/(Fe^{+2}+Fe^{+3})$ ratio of the schists generally decreases with advancing metamorphism in the present metamorphic terrain. This is in harmony with the higher Fe^{+3} contents of hornblendes of zone B.

Miscibility gap between the actinolites and hornblendes

In the central Abukuma regional metamorphism, the change from the actino lites of zone A to the common hornblendes of the higher-grade zones with advancing metamorphism appears to be abrupt. That there exists a compositional gap between the two groups of calciferous amphiboles is suggested by the following observations: (1) The boundary between the actinolite core and hornblende periphery in zoned crystals appears to be sharp in all cases. With increasing grade, the core becomes smaller and finally disappears without losing the sharpness of the boundary. (2) As shown in Fig. 21, index γ of the actinolites and that of the coexisting blue-green hornblendes from the transitional part between zones A and B are in a definite relationship. This indicates that the two amphiboles were probably in equilibrium with each other in these metamorphic grades.

These observations may be regarded as suggesting the existence of a miscibility gap between the two groups of amphibole under the metamorphic conditions

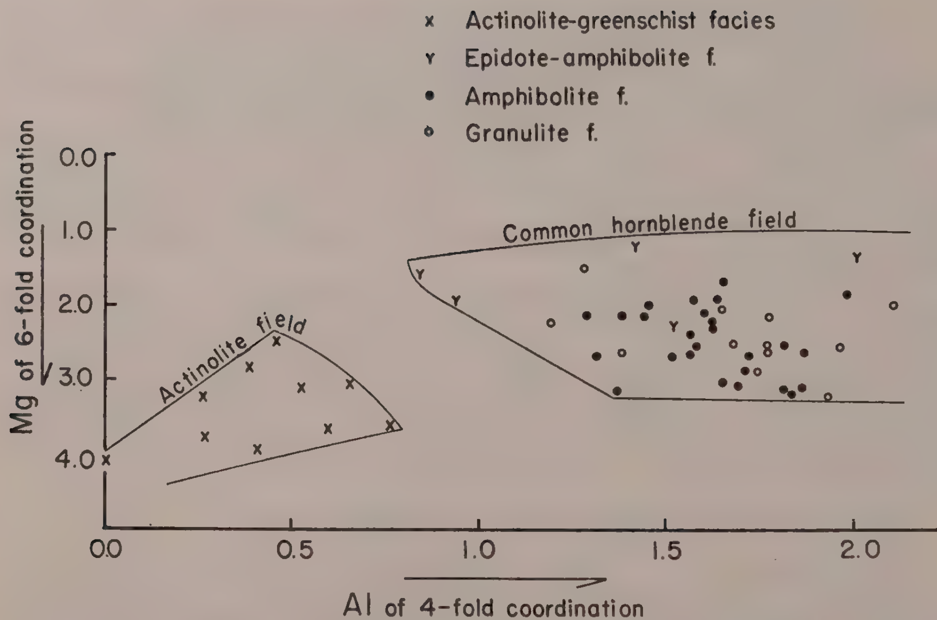

Fig. 24a. Composition fields of calciferous amphiboles from metamorphic rocks of basic and intermediate compositions of the world. The abscissa and ordinate represent the amounts of Al^{IV} and Mg respectively, calculated on the anhydrous basis of O=23.

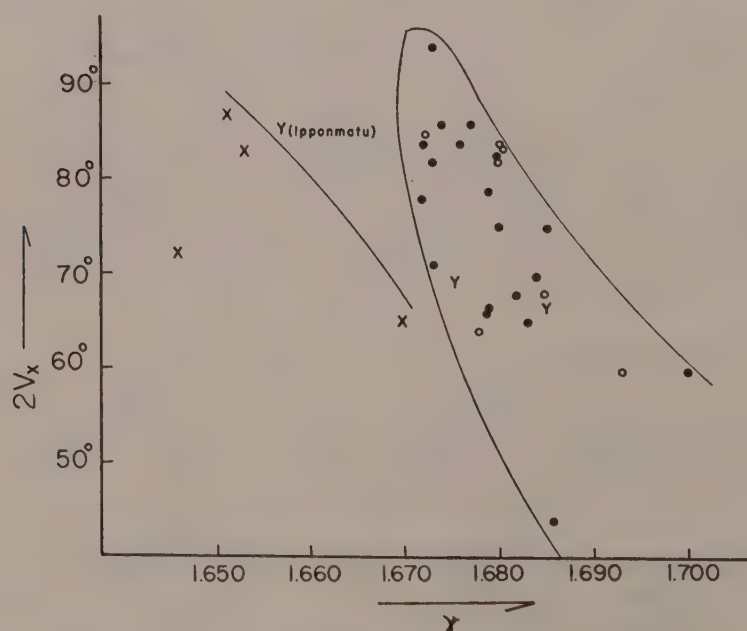

Fig. 24b. 2V-γ relation in the same calciferous amphiboles as in Fig. 24a. Amphiboles of the actinolite-greenschist facies fall in a field distinct from that of amphiboles of the other facies. The Ipponmatu hornblende falls between the two concentration fields, probably because it is exceptionally rich in alkalies.

of the present district. Someone might regard, however, the zonal structure of the amphiboles is due to insufficient diffusion during metamorphic recrystallization and not due to the existence of a miscibility gap. In order to clarify this point, I examined reliable chemical data in the literature on metamorphic calciferous amphiboles. I obtained Fig. 24 which strongly supports the existence of a miscibility gap. All the calciferous amphiboles plotted here are those from metamorphic rocks of basic and intermediate compositions ranging from the actinolite-green schist facies to the granulite facies. Calciferous amphiboles from skarns, metamorphosed iron-formations and other metamorphic rocks of unusual compositions were omitted. The composition field for the amphiboles of the actinolite-greenschist facies is separated by a vacant field from that for the higher grade facies. This vacant space probably corresponds to the miscibility gap. (This statement does not preclude the possibility that the miscibility gap may vanish in some types of metamorphism, of which we have no or few mineralogical data at present.)

One of the coordinate axes of this figure represents the Al^{IV} content and the other the Fe^{+2}–Mg substitution. That the gap becomes very clear in this figure, would show that the Fe^{+2}–Mg substitution is influenced by the Al^{IV} content.

In this figure, the Al^{IV} contents of amphiboles in the common hornblende field do not show any regular variation with rising temperature of their formation. This fact is in the harmony with the observations previously mentioned on the calciferous amphiboles of the present district.

Epidote

Epidote is a chief constituent mineral of low-grade basic and calcic metamorphic rocks of the district. In basic schists, the mineral is commonly present in zone A and the lower-grade part of zone B, whereas in the higher grades it is practically absent among the products of progressive metamorphism. Thus, the boundary between the middle- and the lower-grade parts of zone B can be drawn on the map as the line where epidote disappears from almost all basic rocks. With decrease and disappearance of epidote, the associated plagioclase becomes more calcic rapidly. In basic schists, the mineral under consideration occurs commonly as rounded xenomorphic grains scattered sporadically, and rarely as well-shaped idiomorphic, elongated crystals. Sometimes it shows zonal structure strongly or weakly. The zoned crystals for med during the progressive metamorphism generally has a core with higher birefringence than the periphery.

In calcic metamorphic rocks, epidote appears to occur more persistently up to a higher grade than in basic schists, though it is difficult to decide whether the mineral is stable or not. In calcic rocks, epidote occurs not uncommonly even in zone C where it replaces grandite garnet in network, probably owing to a retrogressive reaction.

The optical angle is useful for distinguishing the monoclinic form from the rhombic and also for determining the composition. So, I measured the optic angles for Na-light on many epidotes only from basic schists as follows:

Zone A

Specimen No. FS 54L2

Grain (1): Lacking in zonal structure, $2V_X=89.5°$ (9 mol. % Fe^{+3}-end member).

Grain (2): Lacking in zonal structure, $2V_X=90°$ (8 mol. %).

Grain (3): Zoned, $2V_X$ (core)$=82°$ (17 mol. %) and $2V_X$ (margin)$=89°$ (10 mol. %).

Specimen No. FS 54A19

Grain (1): Lacking in zonal structure, $2V_X=70°$ (34 mol. %).

Grain (2): Zoned, $2V_X$=75° (26 mol. %) and $2V_X$ (margin)=80° (19 mol. %).
Specimen No. FS 54E22
Grain (1): Lacking in zonal structure, $2V_X$=80° (19 mol. %).
Grain (2): Lacking in zonal structure, $2V_X$=76° (25 mol. %).
Grain (3): Lacking in zonal structure, $2V_X$=76° (25 mol. %).
Specimen No. FS 54E21
Grain (1): Lacking in zonal structure, $2V_X$=73° (28 mol. %).

The transitional grade between zones A and B.

Specimen No. FS 54F12
Grain (1): Lacking in zonal structure, $2V_X$=80° (19 mol. %).
Grain (2): Lacking in zonal structure, $2V_X$=81° (18 mol. %).
Grain (3): Zoned, $2V_X$ (core)=79° (20 mol. %) and $2V_X$ (margin)=89° (10 mol. %).
Specimen No. FS 54F13
Grain (1): Lacking in zonal structure, $2V_X$=71° (33 mol. %).
Grain (2): Lacking in zonal structure, $2V_X$=73° (30 mol. %).
Specimen No. FS 54L5
Grain (1): Lacking in zonal structure, $2V_X$=61° (>40 mol. %).
Grain (2): Lacking in zonal structure, $2V_X$=61° (>40 mol. %).

Zone B

Specimen No. FS 54M5
Grain (1): Lacking in zonal structure, $2V_X$=62° (>40 mol. %).
Grain (2): Lacking in zonal structure, $2V_X$=63° (>40 mol. %).
Specimen No. FS 54E17
Grain (1): Weakly zoned, $2V_X$ (core)=74° (27 mol. %) and $2V_X$ (margin)=76° (25 mol. %).
Specimen No. FS 56071911
Grain (1): Lacking in zonal structure, $2V_X$=77° (24 mol. %).
Grain (2): Lacking in zonal structure, $2V_X$=77° (24 mol. %).
Specimen No. FS 56113001
Grain (1): Zoned, $2V_X$ (core)=60° (>40 mol. %) and $2V_X$ (margin)=73° (28 mol. %).
Grain (2): Zoned, $2V_X$ (core)=67° (40 mol. %) and $2V_X$ (margin)=75° (26 mol. %).
Grain (3): Zoned, $2V_X$ (core)=68° (40 mol. %) and $2V_X$ (margin)=93° (7 mol. %).

The values were obtained mostly by plotting the optic elasticity axes and one of the optic axes on the stereographic net.

As is clear from the above data, the ferric iron content of epidote in basic schists does not show any simple relation with the grade of metamorphism. However, in all the zoned crystals, so far as I have observed, the margin is poorer in ferric iron than the core, without sharp boundary. The general decrease of the $Fe^{+3}/(Fe^{+2}+Fe^{+3})$ ratio of the basic schists with advancing metamorphism (MIYASHIRO, 1958) would be partly related to the decrease of iron content toward the margin.

Clinopyroxene

In calcic rocks, clinopyroxene makes its first appearance in the lower-grade part of zone B, and in all the higher grades it is one of the commonest constituents.

In basic rocks, clinopyroxene appears in zone C as one of the common constituents. Probably, the increase of clinopyroxene in zone C is partly due to the reaction between grandite garnet of calcic bands and lenses and hornblende of the surrounding amphibolite as a result of activated diffusion at elevated temperatures as stated before. Clinopyroxene occurs in all the basic rocks of zone D as one of the decomposition products of hornblende.

Chemical analysis was made on a clinopyroxene from a basic rock of zone C. The result is shown in Table 13. Optical properties of clinopyroxenes from the district are shown in Table 14.

Table 13. Chemical composition of a clinopyroxene from clinopyroxene-amphibolite (Specimen No. FS 54C9), Sekimoto-mura, Taga-gun, Ibaragi Prefecture.

	Wt. %	Mol. prop.	O=6			
SiO_2	49.60	8258	Si 1.910	2.000		
Al_2O_3	2.41	236	Al 0.090			
TiO_2	0.53	66				
Fe_2O_3	1.66	104	Al 0.019			
FeO	13.57	1889	Ti 0.015			
MnO	0.49	69	Fe^{+3} 0.048	1.107		
MgO	9.97	2473	Mn 0.016		2.013	
CaO	21.13	3768	Mg 0.572			
Na_2O	0.43	69	Fe^{+2} 0.437			
K_2O	0.07	7	Ca 0.871			
$H_2O(+)$	0.42		Na 0.032	0.906		
$H_2O(-)$	0.26		K 0.003			
Sum.	100.54		$CaSiO_3$ 46.3			
$2V_Z$=55.5° −56°			$MgSiO_3$ 30.4			
			$FeSiO_3$ 23.2			
α=1.694			99.9			
β=1.702						
γ=1.727			$Fe^{+2}/(Fe^{+2}+Mg)=0.43$			

Note: The associated hornblende was also analysed (Table 7, No. 2).

Table 14. Optical properties of clinopyroxenes.

Zone	Specimen No.	Max. γ	Min. α	β	$2V_Z$
D	FS 54D14'	1.733	1.703	1.711–1.712	59°–60°
	FS 54D12(O)	1.714	1.686	1.693	54.5°–55.5°
	FS 54C8	1.718	1.689	1.697	52.5°–53.5°
C	FS 54C9	1.727	1.694	1.702–1.705	55.5°–56°
	FS 56113015	1.721	1.687	1.698–1.695	56.5°–57°
	FS 56113024	1.723	1.689	1.697–1.701	58°–58.5°
	FS 54D9	1.728	1.687	1.695–1.701	54.5°–55.5°
B	FS 54E11	1.717	1.687	1.695	56.5°–57.5°
	FS 54E8	1.721	1.690	1.698	58°

Note: Max. γ and min. α were determined by the immersion method within the possible error ±0.002, and the range of β was deduced from max. γ and min. α by assuming appropriate values for $(\gamma-\alpha)$.

These data indicate that all the clinopyroxenes found in the district are mainly composed of the diopside-hedenbergite series. The compositions of these pyroxenes were estimated from MUIR's (1951) diagram and plotted on En-Fs-Wo diagram as shown in Fig. 25. According to the figure, *the maximum value of the* $(Mg+Fe^{+2})/Ca$ *ratio of clinopyroxene appears to increase with increasing grade of metamorphism.* This compositional variation is probably due to the dwindling of the miscibility gap within the composition field of En-Fs-Hd-Di with rising temperature. A. MIYASHIRO (1958) gives the analysis of a clinopyroxene from the higher-grade part of zone B. Its composition is in harmony with the above statement.

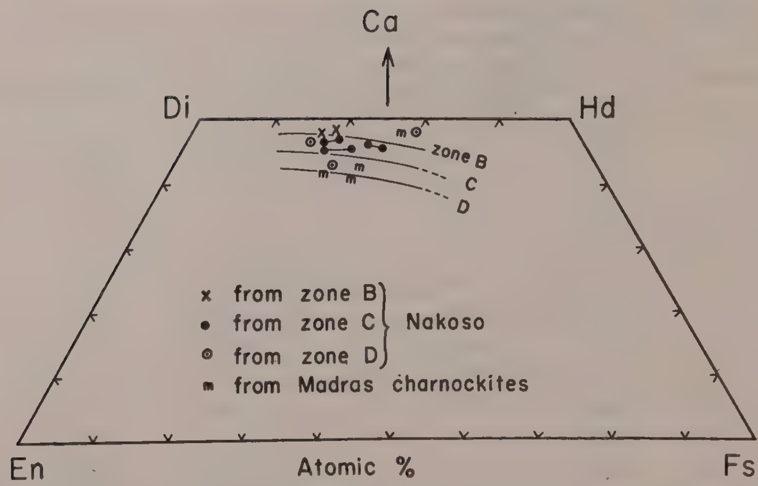

Fig. 25. Chemical compositions of clinopyroxenes from various zones of the Nakoso district and those from charnockites of the Madras district described by HOWIE (1954–55). (The compositions were estimated by MUIR's diagram.) Pairs of solid circles, connected by a line, represent the core and margin of zoned crystals. Three lines represent approximate limits of solid solution in zones B, C, and D.

Orthopyroxene

The occurrence of orthopyroxene distinguishes zone D from all the others. The first appearance of the mineral is recorded from the basic schist located about 25 m. apart from the contact with the gabbro. In rocks in immediate contact with the gabbro, it is completely altered into green hornblende, probably due to the permeation of hydrous residual materials from the gabbro. Exsolution lamellae are absent except in some large crystals in the rocks close to the contact. Brown hornblende is always associated with the orthopyroxene.

Their optical properties and chemical compositions determined from the curve given by H. H. HESS (1952) are shown in Table 15. Thus, all the orthopyroxenes found in the metamorphic rocks of the district are not rich in ferrous iron, but of intermediate compositions.

Table 15. Optical properties and chemical compositions of orthpyroxenes from the metamorphic rocks of the Nakoso district.

Specimen No.	2Vx	Disp.	Comp.
FS 54C11	50°	r<v	44% En.
FS 54C8	50°–53°	r>v	55–59% En.
FS 54D12(40)	50°–54°	r>v	58–62% En.
FS 54A2'	66.5°–68°	r>v	72–74% En.

Note: The optical properties of the monoclinic pyroxene coexisting with the orthopyroxene (Sp. No. FS 54C8) are given in Table 14.

Wollastonite

Wollastonite was found only from the transitional area between zones C and D. Calcic bands and lenses that contain both calcite and quartz are common in zones A and B, but very rare in zone C. Then, wollastonite might have begun to form in some parts of zone C, if there had been rocks of appropriate compositions,

The iron content of wollastonite coexisting with hedenbergite serves as a geological thermometer. A wollastonite-ferrosalite assemblage was found at a locality about 25 m. from the contact with the two pyroxene-hornblende-gabbro. The host rock (Specimen No. FS54D14′) is amphibolite containing ferrosalite bands (about 2 cm. wide), which in turn contain thin intervening wollastonite bands (thinner than 0.5 cm. wide). The wollastonite appears to have been formed in equilibrium with ferrosalite. The optical properties of these minerals are as follows:

Wollastonite: $2V_X=39°$

$\beta_D=1.631\pm0.002$

It is white to the anaided eye and colorless under the microscope. The above data agree well with those of iron-poor wollastonite.

Associated ferrosalite:

$2V_Z=59°$

$\alpha_D=1.703+0.002$

$\gamma_D=1.733+0.002$

Pleochroism: X=light green

Y=slightly yellowish green

Z=light green

The composition of the pyroxene determined from the curve given by I.D. Muir (1951) is $Wo_{46.5}En_{23.5}Fs_{30}$. The $Fe^{+2}\times100/(Fe^{+2}+Mg)$ ratio is 56.1.

In the paragenesis, wollastonite is almost free from ferrous iron, in spite of the abundance of hedenbergite molecules in the coexisting clinopyroxene. Thus the recrystallization temperature of the host rock in the transitional part between zones C and D was not so high enough to introduce ferrous iron into the wollastonite structure in an appreciable amount, even though the available ferrous iron was abundant.

Table 16 gives the chemical compositions of wollastonites and associated pyroxenes of the diopside-hedenbergite series from the Nakoso and other localities.

Table 16. Paragenic relations between wollastonite and clinopyroxene.

Locality	$100\times Fe^{+2}/(Fe^{+2}+Mg)$	
	clinopyroxene	Wollastonite
1. Kanpū	about 70	about 11
2. Skye	67	17
3. Moltinkylä	40	about 2
4. Nakoso	56	about 0

The host rocks:

1. Xenolith included in hornblende-bearing augite-hypersthene andesite, a lava of Kanpū Volcano, Akita Prefecture, Japan (Isshiki, 1954).
2. Hedenbergite skarn, Camas, Malag, Skye. The skarn was formed by the invasion of a Tertiary granite (Tilley, 1948).
3. Skarn from Moltinkylä, Sipoo, Finland (Simonen, 1953).
4. Amphibolite, Ogawa, Nakoso City, Hukusima Prefecture (the present paper).

Biotite

Biotite is one of the commonest costituents of pelitic and psammitic rocks throughout all zones, even in the lowest-grade rocks, and it occurs sometimes in basic rocks, though usually small in amount. In general, the relation between

the color of biotite and metamorphic grade is not clear. However, green biotite occurs not so often but characteristically in the pelitic and psammitic schists of the lowest-grade part of zone B and the still lower grades.

Chemical analysis has been made on a *green* biotite from the lowest-grade part of zone B of the present district. The analysed sample was purified by the isodynamic separator and Clerici solution. The result is shown in Table 17.

Table 17. Green biotite from a biotite schist (Specimen No. FS 54M9 from the lowest-grade part of zone B), Seto, Ogawa-mati, Nakoso City, Hukusima Prefecture. (Analyzed by H. Haramura)

	Wt. %	Mol. prop.	(O, OH)=24			
SiO_2	38.42	6397	Si	5.570	8.00	
TiO_2	1.49	187	Al	2.430		
Al_2O_3	18.26	1791	Al	0.689	1.909	4.927
Fe_2O_3	9.69	607	Fe^{+3}	1.057		
FeO	6.93	965	Ti	0.163		
MnO	0.36	51	Fe^{+2}	0.840	3.018	
MgO	9.46	2346	Mn	0.044		
CaO	0.59	105	Mg	2.043		
Na_2O	2.67	431	Ca	0.091		
K_2O	7.17	761	Na	0.751	2.076	
$H_2O(+)$	4.58	2542	K	1.325		
$H_2O(-)$	0.64		(OH)	4.427		
P_2O_5	0.02	1				
Total	100.28					

$2V \doteqdot 0$ Pleochroism: X = very pale yellow

$\gamma_D = 1.649$ Y = Z = light green

$d_{001} = 10.07$ Å

The comparison of the result with the chemical compositions of many metamorphic biotites reveals that this biotite has the following compositional characteristics;

(1) The Na_2O content of the biotite is extraordinarily high. The Na_2O and K_2O contents are sufficiently reliable, because they were determined by means of the flame photometer of high quality. The high Na_2O content is due to the abundance of paragonite molecule in the biotite. It seems that biotites formed at high temperatures, tend to have high Na_2O content, but the Nakoso biotite was formed at a low temperature, and the high Na_2O content may be due to some unknown chemical factor of the environment.

(2) The SiO_2 content of the biotite is much higher than those of most metamorphic biotites described by A. MIYASHIRO (1958) from the central Abukuma Plateau. The Nakoso biotite was formed at a lower grade than any of MIYASHIRO's biotites. Probably, the SiO_2 content of biotite decreases, that is, the degree of substitution of Si by Al increases in passing from the lowest-grade part of zone B to the higher grades. N. J. SNELLING (1957) suggested a similar relation for biotites of the Dalradian series. However, it seems to me that such a compositional variation takes place only in a very low grade.

(3) The Fe_2O_3 content of the biotite is very high. Biotites having such high Fe_2O_3 contents were reported by A. MIYASHIRO (1958, Table, 8, No. 1) from zone

B, and by F. C. PHILLIPS (1930) from the low-grade green beds of the Scottish Highlands. Thus, the high Fe_2O_3 content of biotite is characteristic of the low grade metamorphism.

A. J. HALL (1941) discussed the relation between the color and composition of biotites and he concluded that the TiO_2 content is responsible for brown color of biotite, the high total iron content is responsible for green color, and the influence of Fe_2O_3 on the color of biotite is not clear. The green biotite from the Nakoso district is poor in FeO and rich in Fe_2O_3. It follows that probably the high contents of Fe_2O_3 as well as FeO induce biotite to have green color. In general, low-grade biotites are low in TiO_2 content, and high in Fe_2O_3 content. On the other hand the FeO^{+2}/MgO ratio admittedly varies widely according to the chemical composition of their host rocks. Therefore, we may consider that the characteristic occurrence of green biotite in low-grade metamorphic rocks is probably due to that biotites in such low grades tend to have low TiO_2 and high Fe_2O_3 contents.

The powder pattern of the analysed green biotite was taken by the Norelco Geiger counter X-ray diffractometer. The results revealed that the analysed material was pure ordinary biotite showing normal reflections, and any chlorite was not admixed.

Muscovite

Muscovite is found in pelitic and psammitic rocks from zone A to the middle-grade part of zone C. It is extremely rare in basic schists in low grades. The optical properties of muscovites are shown in Table 18. Most of their indices and optic angles fall in the ranges: $\gamma=1.598$–1.613, and $2V_X=38°$–$42°$.

Table 18. Optical properties of the metamorphic muscovites of the Nakoso district.

Zone	Host rocks	γ	$2V_X$
A	FS 54E22 (basic)	1.613	not uniaxial
B	FS 54E15 (pelitic)	1.606	39°
B	FS 54E13' (pelitic)	1.604	39°
B	FS 54E13 (pelitic)	1.598	41°
B	FS 54M22 (pelitic)	1.607	46°
B	FS 54A16 (pelitic)	1.607	38.5°
B	FS 56051314 (pelitic)	1.613	38°
B	FS 56051210 (pelitic)	1.600	42°
B	FS 54A11 (pelitic)	1.6115	38°
B	FS 56071801 (pelitic)	1.601	41°
C	FS 56051317 (pelitic)	1.602	35°

A. MIYASHIRO (1958) has shown that the composition field of muscovite becomes smaller with increasing grade of metamorphism.

Chlorite

In basic rocks, chlorite occurs commonly as one of the chief constituents in zone A, though usually less abundant than actinolite. Chlorite, however, decreases in amount with advancing metamorphism and at last, it disappears before the middle of zone B.

In pelitic and psammitic rocks of zone A, it is less abundant than in the

associated basic rocks. In pelitic and psammitic rocks, chlorite disappears at a lower grade than in basic rocks, probably at the entrance to zone B.

Chlorite schists that do not carry biotite nor amphibole were not found in the present district among the products of progressive metamorphism.

Optical properties and basal spacings of chlorites from basic metamorphic rocks of the Nakoso district are given in Table 19.

Table 19. Optical properties and basal spacings of chlorites from basic metamorphic rocks of the Nakoso district.

Zone	Sp. No.	γ_D	Color in the section	Pleochroism	d(005)
B	FS 54A14	1.625	very pale yellow	non	2.81Å
A–B	FS 54L5	1.632	very pale green	non	
A–B	FS 54A18'	1.625	pale green	disc	
A–B	ES 54A19	1.627	pale green	disc	2.81Å
A–B	FS 56071813	1.620	light green	dist	
A–B	FS 55108F12	1.615	pale green	disc	
A–B	FS 54E21	1.628	pale green	disc	2.81Å
A	FS 54L1	1.616	very pale green	non	
A	FS 54L2	1.623	pale green	disc	2.81Å
A	FS 54M20	1.614	pale green	disc	
A	FS 56071911	1.616	pale green	disc	

Notes. non=non-pleochroic; disc=discernible; dist=distinct.

Other Minerals

Cordierite occurs very rarely. Two crystals in a thin section (Specimen No. FS 5601302) from the higher-grade part of zone B are all that I found. These crystals are porphyroblasts in a tourmaline-bearing biotite-quartz schist. They are colorless and carry dusty inclusions along (010) planes and have practically the same indices as quartz. The optic angle over X was about 85°.

Andalusite was found from the lower-grade part of zone C down to the middle-grade part of zone B. However, if highly aluminous rocks had been present throughout the area, andalusite would have been formed also in still lower grades than in the present case.

The mineral occurs as porphyroblasts in two-mica schists with or without quartz and potash felspar. It is probably poor in ferric iron, because it is colorless in thin sections, except in one specimen from the transitional part between zones B and C in which andalusite occurs as zoned crystals with a colorless margin and a slightly reddish core. Crystals of andalusite are free from any inclusions, and are usually surrounded by an aggregate of fine flakes of muscovite which were probably produced by retrogressive change from the marginal part of the crystal itself.

The optical properties are given below:

Specimen No.	α_D	γ_D	$2V_X$
FS 56051210 (zone B)	1.631	1.642	n.d.
FS 54 AB 2 (zone B)	1.633	1.645	85°

Sillimanite has not been found in the present district, probably owing to the absence of aluminous sediments in high grades where sillimanite becomes stable instead of andalusite. Judging from the data in the Gosaisyo-Takanuki district (A. MIYASHIRO, 1958), the transition from andalusite to sillimanite would take place in the lower-grade part of zone C.

Corundum occurs very rarely in highly aluminous pelitic rocks. Under the microscope, such highly aluminous pelitic rocks are composed of a fine alternation of quartzose bands and highly aluminous quartz-free ones, the boundary between the two kinds of bands being sharp. The quartzose bands are composed mainly of quartz with subordinate amounts of muscovite and potash felspar, whereas the highly aluminous bands mainly of muscovite, biotite and plagioclase with subordinate amounts of andalusite, corundum and potash felspar. Corundum occurs only within the aluminous bands and never in contact with quartz. The distance between a corundum and the nearest quartz was measured in several thin sections. The smallest value was 0.28 mm. This indicates that the diffusion of Si as well as Al through a solid medium is very slow even in such a high grade. For the problem of the scope of diffusion, see A. Miyashiro (1958).

Pyralspite garnet. Through the elaborate investigation by A. Miyashiro (1953b), the behavior of pyralspite in the progressive metamorphism in the Gosaisyo-Takanuki district has been clearly known. Probably pyralspites of the Nakoso district are very similar and therefore, no description is needed in this paper.

Tourmaline occurs commonly in pelitic and psammitic rocks and less commonly in basic rocks throughout zones A, B and C. It is in prismatic crystals elongated parallel to c. In most cases c-axis is vertical to the schistosity plane. The pleochroism is usually as follows: parallel to c(E)=colorless to pale pink or yellow and perpendicular to c(O)=light yellowish green to dark green; In zoned crystals, the color of the core is deeper than that of the periphery.

Sphene. In zone A, basic rocks often contain extremely fine-grained unidentified mineral. Probably it is sphene. In zone B, fairly large grains of sphene occur commonly in basic rocks. In zones C and D, sphene decreases in ordinary basic rocks. The Ti content of hornblende is larger in zone C than in zone B, and hence we may consider that the Ti which was in sphene in zone B entered into hornblende in zone C.

In calcic rocks, sphene was not found from zone A. It is, however, one of the commonest constituents in calcic rocks of zones B and C.

Opaque mineral. Sulphide minerals such as pyrite and chalcopyrite are more abundant in basic rocks than in pelitic and psammitic rocks. Hematite occurs up to the lower-grade part of zone B, whereas it does not appear to occur in the still higher grades among the products of progressive metamorphism. Magnetite and ilmenite occur in all zones.

PART II. THE IRITŌNO DISTRICT

1. General Statement

As stated before, the grade of the regional metamorphism in the central Abukuma Plateau increases generally westward, and hence the metamorphic grade is low in the Iritōno district. The Iritōno igneous complex, belonging to the younger group of plutonic rocks in the Abukuma Plateau, intruded into once regionally metamorphosed rocks to produce hornfelses around it. Part II of this paper is concerned mainly with the contact metamorphism caused by the Iritōno igneous complex. A petrographic description of the igneous mass itself is also given briefly.

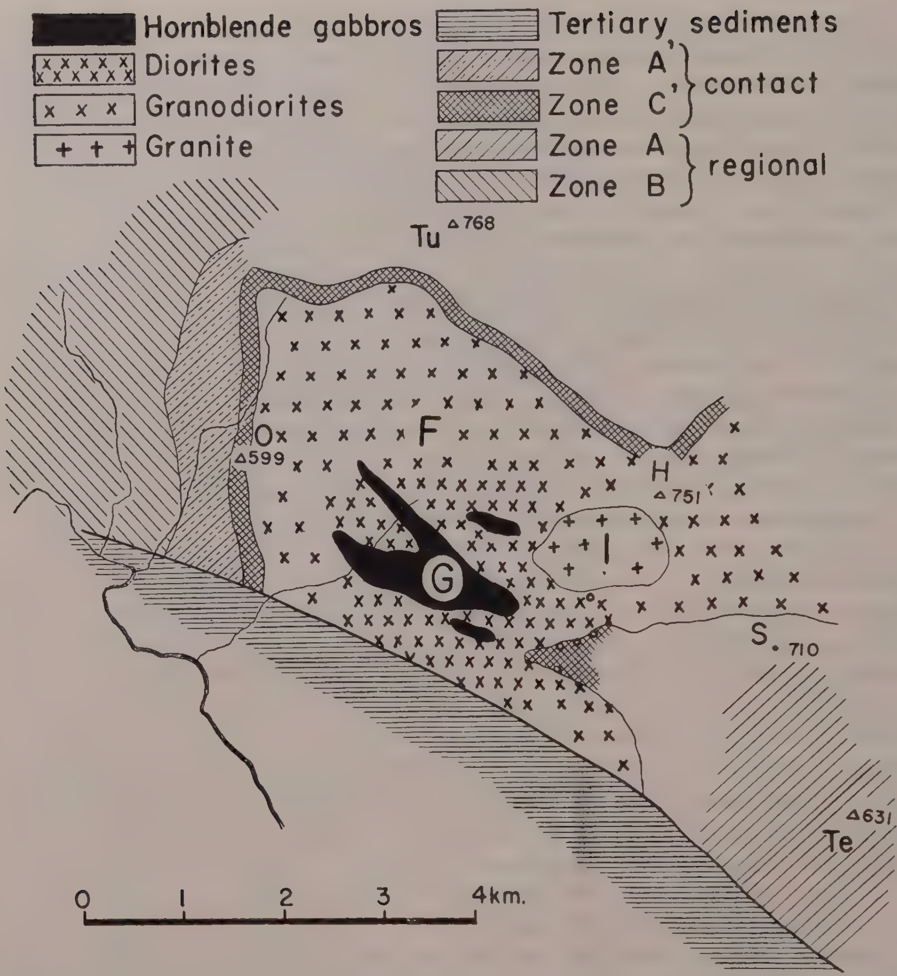

Fig. 62. Geological map of the Iritōno district. G, I, and F represent the G, I, and F masses respectively. H=Hutatuisi-yama, O=Ōzyō-san, S=Sandaimyōzin-yama, Te=Tengu-yama, Tu=Turuisi-yama. Open circles indicate the localities where orthopyroxene was found in schists or in xenoliths. The numerals represent the heights of mountains above sea level.

As shown in Fig. 26, the southern extension of these metamorphic and igneous rocks are cut by a large fault (Iritōno fault, striking N 50°W), to the south of which are exposed Tertiary sediments. In general, the schistosity and bedding planes of the metamorphic rocks trend nearly NS with a vertical dip. The shape of the igneous mass is not stretched parallel to the general trend of the surrounding metamorphic rocks, though locally injection planes are usually concordant with the trend.

2. The Iritōno Igneous Complex

Introductory Statement

The complex is composed of three units, which are shown on the geologic map, Fig. 26, under the designations: G masses, F mass and I mass. The G

masses consist mainly of hornblende-gabbros, the F mass mainly of granodiorites and the I mass mainly of granites. Besides them, there are many dikes and sheets intruding the igneous and adjacent metamorphic rocks, and probably they have a close genetical relation to the hornblende-gabbros of the G mass.

The F mass which occupies most of the exposed area of the present complex, contains abundant dark inclusions. They are commonly spherical and rarely elongated in form, though they do not show any fluxional arrangement. No parallel structure is present in the mass. These characteristics observed in field are compared with those of the Tabito igneous complex in Table 20. The distinctive features of the two complexes are in harmony with the statement of M. Gorai (1944).

Table 20. Comparison of the Tabito and Iritōno igneous complexes.

	The Tabito complex	The Iritōno complex
Shape of the complex	Stretched concordantly in the direction of the general trend.	Discordant; only locally concordant with the general trend.
Dark inclusion:		
Amount	Very large.	Not so lorge.
Shape	Commonly oval or streaky.	Commonly spherical or rounded.
Fluxion structure	Remarkable.	Utterly lacking.
Parallel structure	Very remarkable in some portions of the mass.	Utterly lacking throughout the mass.

The G Masses

The G masses are a group of small plutonic bodies which resulted from composite intrusion of basic magmas. The masses are composed of three different rock types: fine-grained hornblende-porphyrite (denoted by G1), medium- to coarse-grained hornblende-gabbros (G2) and hornblende-gabbro pegmatite (G3). Generally speaking, the grain-size increases towards the center of each mass. Fig. 27 represents a schematic cross section of a relatively large mass of this group. The boundary between G1 and the adjacent diorite is very sharp. The boundary between G1 and the gabbroic interior is also fairly district, whereas that between G2 and the pegmatitic facies G3 is gradational and G3 occurs as irregular patches or pockets near the center of the mass. Probably G1 represents the chilled facies of a basic magma which intruded a little earlier than the intrusion of G2.

Petrography of the interior of the mass (G2 and G3)

The grain-size is varied largely in the interior, without marked difference

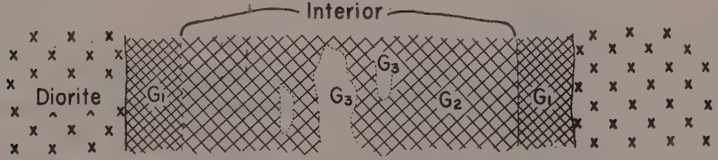

Fig. 27. Simplified cross-section of the gabbro mass G, illustrating the distribution of different rock types.
G1: fine-grained hornblende porphyrite.
G2: medium- to coarse-grained gabbro.
G3: gabbro pegmatite.

in mineral composition. The interior is composed of hornblende-gabbros which consist mainly of basic plagioclase and brown hornblende with small amounts of cummingtonite, biotite, quartz and opaque mineral. Most plagioclases show three-layered normal zoning with a core of calcic bytownite, a mantle of labradorite and a rim of sodic andesine. A typical specimen is described below.

Biotite-hornblende-gabbro (Specimen No. FS 56081904)

Texture: fine- to medium-grained, non-porphyritic.

Chief const.: plagioclase (showing three-layered normal zoning; the core=An_{87-82}, the mantle=An_{55-51}, and the rim=An_{32-27}), hornblende (showing two-layered zoning; the core with Z=yellowish brown, 2V=90°, and γ=1.684; the margin with Z=dull green and $2V_X$= 78°)>>>biotite (β=1.654), quartz>cummingtonite (Z=pale green; idiomorphic crystals sometimes embraced by the hornblende).

Accessory const.: opaque mineral, apatite, chlorite.

Petrography of the marginal part of the mass (G1)

The marginal part is composed of basic diorite-porphyrite. The petrographical characters are similar throughout the marginal part. A typical specimen of G1 is described below.

Basic diorite-porphyrite (Specimen No. FS 56112409)

Texture: fine-grained and weakly porphyritic with phenocrysts of hornblende and plagioclase, both 1 to 2 mm. in length and in good crystal form. The groundmass consists of lath-shaped plagioclases with fairly distinct flow arrangement, together with interstitial green hornblende and biotite.

Chief const.: plagioclase (showing remarkable normal zoning; the core=An_{67} and the rim An_{40})>hornblende (Porphyritic crystals are of brown hornblende with a thin rim of green one. Groundmass crystals are similar in optical properties to the green rim of the porphyritic ones)>>biotite.

Accessory const.: opaque mineral>>>>>apatite.

The F Mass

The F mass is the largest of the three units composing the Iritōno complex. The rock ranges in chemical composition from granodiorite to basic diorite. The basicity increases gradually toward the southeast. Neither intrusive relation nor sharp boundary between the constituting rock types has been observed. The color of the rocks shows a good correspondance to the microscopic features: as the color becomes darker, the ratio of hornblende to biotite increases, the plagioclase becomes more calcic and the Z-axial color of hornblende becomes more brownish. The F mass contains a fairly abundant dark inclusions, 20–30 cm. in diameter. They are distributed rather evenly throughout the mass, and have no tendency to concentrate in basic portions of the mass. Most of dark inclusions have been digested considerably. The rocks of the present mass are divided into two groups on the geological map on the basis of petrographic characters: (1) granodiorites and (2) diorites.

(1) *Granodiorites*

The granodiorites are predominant in the western part of the mass. The rocks are commonly coarse-grained and non-porphyritic, and are composed mainly of sodic plagioclase, quartz, microcline and biotite with a subordinate amount of hornblende. The hornblende is always less abundant than the biotite in the rocks belonging to this category. The hornblende is green with a slightly bluish tinge. The plagioclase shows two-layered zoning with a core of sodic andesine and a margin of oligoclase. Small amounts of zircon, allanite, sphene, apatite and opaque mineral were also observed. A typical specimen is described below.

Hornblende-bearing biotite-granodiorite (Specimen No. FS 56112401)

Texture: non-porphyritic and granitic.

Chief const.: plagioclase (idiomorphic, showing two-layered zoning; the core=An_{35-33} and the margin=An_{27-16}), quartz>>potash felspar (microcline-perthites showing well-developed perthitic and fine quadrille twinning max. $\gamma=1.527$ and min. $\alpha=1.519$), biotite (embracing a lot of sphene grains, $\beta=1.635$)>hornblende ($2V_X=64°$, $\gamma=1.667$, Z=slightly bluish green).

Accessory const.: sphene, opaque mineral.

(2) *Diorites*

The rocks occur in southeastern parts of the mass. They are commonly coarse-grained and non-porphyritic. The amount of hornblende exceeds that of biotite. The rocks carry plagioclase, hornblende, biotite and quartz as chief constituents and are free from potash felspar. Cummingtonite is a common constituent of this type. The plagioclase shows strong zoning in normal order. A typical specimen is described below.

Biotite-hornblende-quartz-diorite (Specimen No. FS 56091604)

Texture: medium-grained, non-porphyritic, granitic.

Chief const.: plagioclase (usually with two- or three-layered zonal structure; in a three-layered crystal, the core=An_{85-80}, the mantle=An_{55-52}, and the rim An_{44-37}; in a two-layered crystal, the portion corresponding to the above core is lacking), hornblende (poikilitic, often enclosing the cummingtonite in the interior; $2V_X=72°$, Z=greenish brown)> biotite (poikilitic)>quartz>>cummingtonite (sometimes embraced by the hornblende and sometimes as isolated crystals).

Accessory const.: opaque mineral, apatite, chlorite (derived from hornblende).

The I Mass

The I mass is fairly uniform, being composed of pyralspite-biotite granite with coarse- to medium-grained granitic texture. Constituent minerals are quartz and microcline with a subordinate amount of sodic plagioclase. Much smaller amounts of pyralspite, biotite and muscovite are also contained. Many minute crystals of zircon are included in the biotite. This mass is free from any dark inclusion. The actual contact with the F mass has not been observed yet, but the present mass seems to be an acid pocket within the F mass. A typical specimen from the mass is described below.

Pyralspite-biotite-granite (Specimen No. FS 56091610)

Texture: medium-grained, granitic.

Chief const.: quartz, potash felspar (slightly turbid microcline-perthite)> plagioclase (oligoclase)>>>biotite ($\beta=1.651$), pyralspite>muscovite (sporadically present within plagioclase crystals).

The Dikes

A number of porphyrite dikes intrude the igneous mass F and the adjacent metamorphic rocks. Their width varies largely, ranging from 1 to over 50 m. All these dikes clearly show chilled margins which indicate that their intrusions were later than that of the F mass. Considering that such porphyrite dikes are confined to the F mass and adjacent area, they have surely been comagmatic with the Iritōno ingeous complex. In mineral composition, these dikes resemble to one another and also to the marginal facies of the gabbro mass G (G1). There similarities suggest that these dikes are in very close genetic relation with the gabbro mass. A typical dike is described below:

The dike to be described intrudes the diorite at a locality 2.5 km. northeast

of Tennō. It is 50 m. in width and trends N 70°W with a dip of 70° to the south. It is composed of chilled margins about 40 cm. in width and a coarser interior. To the unaided eye, both parts are dark, non-porphyritic and massive.

Chilled margins (Specimen No. FS 56081909)

Texture: non-porphyritic, and the lath-shaped plagioclases and prismatic hornblendes show weak flow arrangement.

Chief const.: plagioclase (weakly zoned with a thin sodic rim and a core of An_{68})> hornblende (Z=slightly bluish green)>biotite.

Accessory const.: opaque mineral.

Interior (Specimen No. FS 56081910)

Texture: lacking in flow arrangement and coarser than the chilled facies.

Chief const.: plagioclase (showing two-layered zoning with a thin sodic rim and a core of An_{67}), hornblende (showing zonal coloring with a core of Z=brown, $2V_X=88°$, and a rim of Z=slightly bluish green, $2V_X=60°–63°$ and $\gamma=1.679$)>>>biotite.

Accessory const.: opaque mineral.

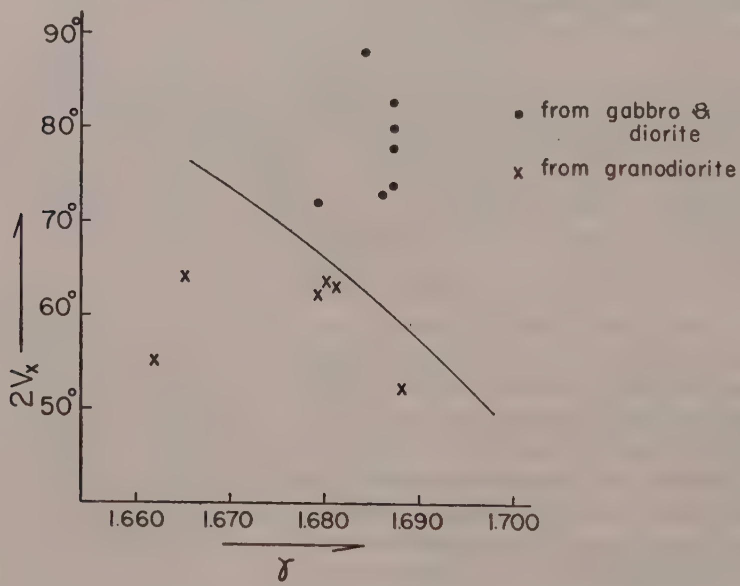

Fig. 28. Optical properties of hornblendes from various rocks of the Iritōno igneous complex.

Optic angles of hornblendes from the Iritōno igneous complex are plotted against index γ with the result shown in Fig. 28. The line corresponds to the line p–p in Fig. 20.

3. Regional Metamorphism in the Iritōno District

The schistosity trends NS with a vertical dip, and is parallel to the bedding planes. In general, schistosity and microfolding do not develop so well in the present district as in the Nakoso. The regional metamorphism in the area to the west of the Iritōno igneous complex was of the grade of zone B (probably not so higher part of zone B), whereas that in the area to the east was of the grade of zone A.

The boundary between zones A and B in the regional metamorphism can be

laid down on the map only roughly. Probably it passed in the NS direction through the site of the present igneous mass. This boundary lies just on the northern extension of the corresponding boundary in the Gosaisyo-Takanuki district.

Mineral assemblages and other characters of the regional metamorphic rocks in zones A and B in the present district are practically identical to those in the corresponding zones in the Nakoso and Gosaisyo-Takanuki districts. Therefore, no description would be needed on them.

4. Introductory Statement on the Iritōno Contact Metamorphism

(1) *Original rocks*

Metamorphic rocks of the present district were derived mainly from basic igneous materials and subordinately from psammitic rocks. Calcic bands or lenses are rather rare and pelitic rocks are still rarer.

(2) *Basis of zonal mapping*

The contact aureole of the Iritōno intrusive mass was divided into three zones, A′, C′, and D′ in the order of increasing grade of metamorphism. The zonal mapping was made after the same scheme as in the regional metamorphism of the Nakoso and Gosaisyo-Takanuki districts; zone A′ is characterized by the exclusive presence or the predominance of actinolite among calciferous amphiboles in basic rocks, zone C′ is characterized by the presence of green to brown hornblende and zone D′ is characterized by the entrance of orthopyroxene. Thus, zones A′, C′ and D′ correspond to regional metamorphic zones A, C and D respectively. The zone corresponding to regional metamorphic zones B is practically lacking. Blue-green hornblende, characteristic of zone B, occurs only in a subordinate amount in the highest-grade part of zone A′.

(3) *Distribution of the metamorphic zones*

Fig. 26 shows the distribution of zones A′ and C′ around the Iritōno igneous complex. As is clear in the map, the thermal effects can be noticed as far as 700–800 meters from the western contact of the Iritōno mass. The widths of the zones A′ and C′ are about 500 and about 300 meters respectively. The occurrence of orthopyroxene-bearing hornfelses is confined to a narrow zone, several meters in width, in direct contact with the diorites. The localities where orthopyroxene-bearing hornfelses were found are marked with open circles. Orthopyroxene was not found in contact with more acidic rocks (i. e. granodiorites). Xenoliths included in the diorites are of orthopyroxene-bearing hornfels, whereas those in the granodiorites are of hornfels representing the grade of zone C′. Thus, the local difference in the basicity within the F mass probably corresponds to a difference in their temperatures at the time of emplacement; *the more basic magma has higher emplacement temperature than the more acidic one*, similarly as in the Tabito igneous complex.

(4) *Structure and grain-size*

Macroscopically, as the contact metamorphism advances, the schistosity fades away and the rocks become more compact and massive. The direction of the pre-existing schistosity is now recognized as cracks. The hardness of rocks increases suddenly as the first trace of the contact-metamorphic recrystallization

becomes perceptible under the microscope and the contact-metamorphic rocks of zone A′ are harder than regional-metamorphic rocks of zone B.

Microscopically, parallelism of minerals is preserved in the rocks of zone A′, whereas in the rocks of higher grades, hornfels texture develops. Grain-size increases fairly regularly with approach to the contact. Fig. 16 shows schematically the relation between the grain-size and the metamorphic grade in the present district in comparison with that in the Nakoso. The grain-size in the corresponding zones is large in the Gosaisyo-Takanuki metamorphic rocks, intermediate in the Nakoso and small in the present metamorphic rocks.

(5) *Degree of recrystallization*

In zone A′, the schists which had been regionally metamorphosed in the grade of zone B were later subjected to retrogressive recrystallization into the grade of zone A′ during the contact metamorphism. It is noteworthy that the retrogressive recrystallization is nearly complete. This suggests that recrystallization of basic rocks takes place generally in such a short time and at such a low temperature as zone A′ probably suffered. It is noteworthy too that plagioclases and calciferous amphiboles of the present contact-metamorphic aureole do not show such marked zonal structure as in zones B and C of the regional metamorphism. The development of zoned crystals in regional-metamorphic rocks indicates that the rocks, which were once recrystallized at lower temperature, were later adjusted to the conditions of higher grades in response to rising temperature. Lack of zoned crystals in contact metamorphic rocks of the district may suggest that recrystallization took place at a single stage near the culmination of the contact metamorphism.

5. Petrology of Metamorphic Rocks

(1) *Zone A′*

Main types of psammitic hornfelses of zone A′ are as follows: (1) pyralspite-biotite-plagioclase-quartz-hornfels, (2) biotite-plagioclase-quartz-hornfels, and (3) muscovite-biotite-quartz-hornfels. Type (2) is predominant. The rocks of these types may contain tourmaline, apatite and dust of opaque minerals.

Main types of basic metamorphic rocks in this zone are (1) actinolite-plagioclase (±quartz) hornfels and (2) chlorite-actinolite-plagioclase (±quartz) hornfels. Both types may carry opaque mineral and biotite together with an unidentified sphene-like grains.

Neither epidote nor zoisite were recognized under the microscope in basic hornfelses of zone A′. It is noteworthy that epidote is absent in ordinary basic rocks of zone A′ of the contact aureole, whereas it is abundant in zone A of the regional metamorphism. The absence of epidote is closely connected with the very high An contents of the associated plagioclases. In basic rocks of zone A′, the plagioclase coexisting with actinolite is commonly andesine and not rarely labradorite, and hence it is much more calcic than the plagioclases of basic rocks in regional metamorphic zone A. Thus, *the assemblage actinolite-labradorite is characteristic of this zone of contact metamorphism.*

The actinolites are usually fibrous and their optical properties are similar to those of the actinolites of regional metamorphic zone A.

Clinopyroxene occurs stably in calcic rocks down to the higher-grade part of zone A′. Epidote is one of the common constituents in the calcic rocks of zone A′.

In basic rocks of the highest-grade part of zone A′, a small amount of blue-green hornblende occurs in association with actinolite. Usually it forms sporadic pools in actinolite-hornfelses. The absence of a typical zone that is characterized by the abundant development of blue-green hornblende, is another remarkable feature of the contact aureole.

(2) *Zone C′*

Psammitic hornfelses observed in zone C′ are classified into the following types: (1) biotite-pyralspite-plagioclase-quartz-cummingtonite-hornfels, (2) quartz-plagioclase-biotite-cummingtonite-hornfels, (3) quartz-hornblende-biotite-cummingtonite-hornfels and (4) pyralspite-biotite-tourmaline-hornfels.

Two pyralspites from psammitic metamorphic rocks of zone C′ were examined by X-ray method. One from pyralspite-cummingtonite-biotite (γ=about 1.648)-andesine-quartz-schist (FS 56082035) gave a=11.54 A. The other from pyralspite-biotite (γ=about 1.648)-andesine-quartz-schist (FS 56082030) gave a_o=11.53 A. They both are probably almandine.

Basic hornfelses of this zone may be classified into the following types: (1) hornblende-plagioclase (±quartz) hornfels, (2) hornblende-clinopyroxene-plagioclase-biotite-hornfels, and (3) hornblende-cummingtonite-plagioclase-biotite-hornfels. The Z-axial color of hornblendes of zone C′ is various ranging from brownish green to brown.

(3) *Zone D′*

Observed basic hornfelses of this zone are as follows: (1) orthopyroxene-hornblende-plagioclase (±cummingtonite) hornfels, and (2) orthopyroxene-clinopyroxene-hornblende-biotite-quartz (±cummingtonite) hornfels. (Symbol ± means "with or without.") The composition of orthopyroxene is about $En_{60}Fs_{40}$.

Boulders of calcic rocks rich in wollastonite, which are supposed to have been derived from zones C′ and/or zone D′ were abundantly found at some localities near the contact, 2 km. SSW of Hutatuisi-yama. The mineral assemblage of these rocks is calcite-grandite-wollastonite-clinopyroxene.

PART III. COMPARISON OF THE METAMORPHISMS OF THE IRITŌNO, NAKOSO AND OTHER DISTRICTS

1. Comparison of the Contact Metamorphism of the Iritōno District with the Regional Metamorphism of the Nakoso District

The contact metamorphism of the Iritōno district produced a similar series of zones as the regional metamorphism of the Nakoso district, though the zone corresponding to zone B is practically lacking in the former. Both metamorphisms are similar in the kinds of minerals produced. However, there are marked differences in character between the two metamorphisms. They will be summarized below.

First, epidote does not occur in the basic rocks of contact-metamorphic zone A′, whereas the mineral is one of the most common constituents of the regional metamorphic zone A. The absence of epidote in the ordinary basic rocks of contact-metamorphic zone A′ is genetically related to the presence of calcic

plagioclases. *The plagioclases coexisting with epidote in regional metamorphic zone A are albite or oligoclase, whereas the plagioclases of the basic rocks in contact-metamorphic zone A′ are andesine or labradorite.* Thus, zone A is characterized by the assemblage actinolite-albite or oligoclase and zone A′ is characterized by the assemblage actinolite-andesine or labradorite.

Secondly, *the zone where basic rocks are composed wholly or mainly of blue-green hornblende and plagioclase is not present in the contact aureole, whereas such a zone develops extensively in the Nakoso regional metamorphism.*

Above mentioned differences between the two metamorphisms would be attributed to the differences between the physical conditions prevailing during recrystallization, as to be explained below.

The absence of epidote in the basic rocks of contact-metamorphic zone A′ is attributed to the low rock pressures prevailing. The reaction in ordinary basic rocks to produce actinolite may be written as follows:

$$\underset{\substack{\text{Chlorite} \\ (211\text{ cc})}}{Mg_5Al_2Si_3O_{10}(OH)_8} + \underset{\substack{\text{Epidote} \\ (6\times 141\text{ cc})}}{6Ca_2Al_3Si_3O_{12}(OH)} + \underset{\substack{\text{Quartz} \\ (7\times 22.4\text{ cc})}}{7SiO_2}$$

$$\rightleftarrows \underset{\substack{\text{Tremolite} \\ (271\text{ cc})}}{Ca_2Mg_5Si_8O_{22}(OH)_2} + \underset{\substack{\text{Anorthite} \\ (10\times 101\text{ cc})}}{10CaAl_2Si_2O_8} + \underset{\text{Water}}{6H_2O} \quad \ldots\ldots\ldots (1)$$

In the above equation, the right-hand side represents the typical assemblage of basic rocks in contact-metamorphic zone A′. The total volume of the solid phases of the left-hand side is 1214 cc and that of the right-hand side is 1281 cc. Thus, the formation of epidote is favoured by higher rock pressures and lower temperatures. On the contrary the formation of calcic plagioclase is favoured by lower rock pressures and higher temperatures.

In the ordinary basic metamorphic rocks of the central Abukuma Plateau, the $Ca/(Mg+Fe^{+2})$ ratio ranges from 1/2 to 1 (see A. MIYASHIRO, 1958), whereas in the above equation the ratio is 2.4. Therefore, in ordinary basic metamorphic rocks, the displacement of the reaction toward the right results in the complete disappearance of epidote rather than chlorite and the produced assemblage is chlorite-actinolite-calcic plagioclase, which is a typical assemblage of contact-metamorphic zone A′. On the other hand, the most predominant assemblage of regional metamorphic zone A is actinolite-chlorite-epidote-sodic plagioclase, the above reaction having gone markedly toward the left.

In the Iritōno contact aureole, blue-green hornblende develops extremely poorly. In other words, actinolite was transformed with increasing grade of the contact metamorphism almost directly into common hornblende with brown Z-axial color, characteristic of zone C′. The stage of blue-green hornblende is practically lacking. The reaction to produce common hornblende from actinolite may be regarded as having been delayed in the Iritōno contact metamorphism, until the metamorphism advanced to the grade where brown hornblende becomes stable instead of blue-green one. The delayed appearance of common hornblende may be also attributed to low rock pressures prevailing during the recrystallization.

As mentioned previously, common hornblende is composed mainly of tschermakite, sodatremolite and edenite molecules, actinolite molecule aside. If the entry of these three molecules into actinolite is not favoured under certain circumstances, actinolite will persist to higher grades without transforming into

common hornblende. The following equations jointly represent the transformation of actinolite into common hornblende:

$$\underset{\substack{\text{Tremolite}\\(271\text{ cc})}}{Ca_2Mg_5Si_8O_{22}(OH)_2}+\underset{\substack{\text{Albite}\\(102\text{ cc})}}{NaAlSi_3O_8}\rightleftarrows\underset{\substack{\text{Edenite}\\(267\text{ cc})}}{NaCa_2Mg_5AlSi_7O_{22}(OH)_2}+\underset{\substack{\text{Quartz}\\(4\times 22.4\text{ cc})}}{4SiO_2}\quad\ldots\ldots(2)$$

$$\underset{\substack{\text{Tremolite}\\(271\text{ cc})}}{Ca_2Mg_5Si_8O_{22}(OH)_2}+\underset{\substack{\text{Albite}\\(2\times 102\text{ cc})}}{2NaAlSi_3O_8}$$

$$\rightleftarrows\underset{\substack{\text{Sodatremolite}\\(273\text{ cc})}}{Na_2CaMg_5Si_8O_{22}(OH)_2}+\underset{\substack{\text{Anorthite}\\(101\text{ cc})}}{CaAl_2Si_2O_8}+\underset{\substack{\text{Quartz}\\(4\times 22.4\text{ cc})}}{4SiO_2}\quad\ldots\ldots\ldots\ldots(3)$$

$$\underset{\substack{\text{Tremolite}\\(271\text{ cc})}}{Ca_2Mg_5Si_8O_{22}(OH)_2}+\underset{\substack{\text{Chlorite}\\(2\times 211\text{ cc})}}{2Mg_5Al_2Si_3O_{10}(OH)_8}+\underset{\substack{\text{Anorthite}\\(8\times 101\text{ cc})}}{8CaAl_2Si_2O_8}$$

$$\rightleftarrows\underset{\substack{\text{Tschermakite}\\(5\times 260\text{ cc})}}{5Ca_2Mg_3Al_4Si_6O_{22}(OH)_2}+\underset{\text{Water}}{4H_2O}\quad\ldots\ldots\ldots\ldots(4)$$

$$\underset{\substack{\text{Tremolite}\\(271\text{ cc})}}{Ca_2Mg_5Si_8O_{22}(OH)_2}+\underset{\substack{\text{Chlorite}\\(14\times 211\text{ cc})}}{14Mg_5Al_2Si_3O_{10}(OH)_8}+\underset{\substack{\text{Epidote}\\(24\times 141\text{ cc})}}{24Ca_2Al_3Si_3O_{12}(OH)}+\underset{\substack{\text{Quartz}\\(28\times 22.4\text{ cc})}}{28SiO_2}$$

$$\rightleftarrows\underset{\substack{\text{Tschermakite}\\(25\times 260\text{ cc})}}{25Ca_2Mg_3Al_4Si_6O_{22}(OH)_2}+44H_2O\quad\ldots\ldots\ldots\ldots(5)$$

In these equations, the left-hand side represents lower temperatures than the right-hand side*. In equation (2), the total volume of solid phases of the left-hand side is 373 cc and that of the right-hand side is 357 cc. (In this calculation, the specific gravity of edenite is assumed to be 3.06 after A. N. WINCHELL (1951). The solid phases of the right-hand side have a smaller volume than those of the left-hand side, provided that the specific gravity of edenite is larger than 2.88. The specific gravity of edenite can not be smaller than that of tremolite, 2.98, as the variation of the cell volume of calciferous amphiboles with their composition is extremely small and edenite has a much larger molecular weight than tremolite.)

In equation (3), the total volume of the solid phases of the left-hand side is 475 cc and that of the right-hand side is 463 cc, provided that the specific gravity of sodatremolite is 3.00. If the specific gravity of sodatremolite is 2.94, both sides have the same volume. Then, inasmuch as the specific gravity of sodatremolite is larger than that of tremolite, the solid phases of the right-hand side have a smaller volume than those of the left-hand side.

In equations (4) and (5), the total volumes of the solid phases of the left-hand side are 1501 cc and 7236 cc respectively, and that of the right-hand side are 1300 cc and 6500 cc respectively, if we assume the specific gravity of tschermakite to be 3.13 after A. N. WINCHELL (1951). Thus, in these equations also the solid phases of the right-hand side have a smaller volume than those of the left-hand side.

Thus, in all the four reactions, the transformation temperatures are lower

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* In these equations, edenite, sodatremolite and tschermakite of the right-hand sides represent molecules in common hornblendes. Therefore, the fictive specific gravities of these molecules are not identical to the actual ones of the corresponding separate phases of amphiboles. In the following discussions, however, it is assumed that the differences are not so large as to change the conclusions. This assumption is probably justified, because the variations of cell dimensions of hornblende with composition are very small.

under higher solid pressures. Accordingly, the formation of common hornblende from actinolite should be promoted under higher solid pressures. From these considerations, the delayed appearance of common hornblende in the Iritōno contact metamorphism can be taken as suggesting that the solid pressure was lower in that metamorphism than in the regional metamorphism of the Nakoso district.

On the other hand, the metamorphism of the Nakoso district is practically identical to that of the Gosaisyo-Takanuki district in all the mineralogical and textural characters of the metamorphic rocks. The regional metamorphism of these two districts may be jointly called the *central Abukuma regional metamorphism.*

It follows that the gabbro masses En and Es of the Nakoso district as well as the batholith W, were emplaced under conditions similar to those prevailing during the regional metamorphism of the Nakoso and Gosaisyo-Takanuki districts, probably at or immediately after the culmination of the regional metamorphism. On the other hand, the Iritōno igneous complex is interpreted as having been emplaced after the uplift and denudation of the Abukuma Plateau. The rock pressure at the time of intrusion of the Iritōno igneous complex and of the contact metamorphism was much lower than that prevailing during the regional metamorphism of the Nakoso and Gosaisyo-Takanuki districts.

M. GORAI (1944) and I. WATANABE et al. (1955) classed the gabbro masses En and Es into the younger group of intrusives. However, it is clear from these results that the gabbro masses belong to the older group.

2. The Alkali Contents of Calciferous Amphiboles in Relation to Types of Metamorphism

The general increase of the alkali contents of common hornblendes in quartz-free basic rocks with advancing regional metamorphism in the central Abukuma Plateau has been mentioned before. In this section, these alkali contents of hornblendes in the central Abukuma regional metamorphism will be compared with those of hornblendes in a few other metamorphic terrains.

Comparison of the central Abukuma Plateau with the Madras district, India

In the Madras district is exposed various charnockites belonging to the granulite and contiguous facies. Recently, we had much mineralogical data of the area, R. A. HOWIE (1954–55) analysed five hornblendes from various charnockites in the district. Their alkali contents and the modes of the host rocks are shown in Table 21.

Hornblende M_1 that is from a quartz-free basic rock and associated with andesine has the highest alkali content among them. The alkali contents of Madras hornblendes are generally higher than those of 'zone C' hornblendes in Abukuma, and the highest value slightly exceeds the highest value of 'zone C' hornblendes of the Abukuma. However, the highest value from the Madras district is lower than that for the glaucophanitic metamorphic terrains.

Comparison of the central Abukuma Plateau with the Grampian Highlands

The petrography of basic metamorphic rocks of the central and southwest Highlands of Scotland was given by J. D. H. WISEMAN (1934) in some detail. He

Table 21. Alkali contents of hornblendes and modes of the host rocks from the charnockite area in Madras, India, after R. A. HOWIE (1954–55). (Alkali contents represented on the anhydrous basis of O=23.)

	M_1	M_2	M_3	M_4	M_5
(Na+K) contents of hornblendes	0.842	0.827	0.676	0.743	0.832
Modes of the host rocks					
Quartz	——	——	——	6.1	20.7
K-felspar	——	——	——	3.8	33.5
Plagioclase	45.0 (and.)	37.8 (lab.)	——	52.9 (and.)	36.6 (and.)
Hornblende	0.9	9.3	8.7	1.4	1.7
Biotite	——	——	——	7.9	——
Hypersthene	25.2	30.0	56.4	5.5	3.4
Augite	24.8	19.4	25.4	13.7	——
Others (spinal, apatite and ores)	4.1	3.5	9.6	5.7	4.1

Host rocks.
M_1: Hypersthene-diorite of the charnockite series, Pallavaram, Madras.
M_2: Norite of the charnockite series, Nagarmalai, Salem, Madras.
M_3: Pyroxenite of the charnockite series, Pammal Hill, Pallavasa, Madras.
M_4: Intermediate rock of the charnockite series, Salem, Madras.
M_5: Intermediate rock of the charnockite series, Ambagamudan Pothai, Tinnevelly district, Madras.

analysed three calciferous amphiboles, one from his "low-grade zone" (including the chlorite and biotite zones) and the remainning two from the garnet zone. The former amphibole is ordinary actinolite, the Na, Al^{IV} and Al^{VI} contents being small, whereas the latter amphiboles are common hornblende. The alkali contents of these common hornblendes are shown in Table 22, together with the molecular compositions calculated on the rule previously proposed (p. 178).

As shown in the table, these hornblendes contain some amounts of the glaucophane molecule. In this respect they are different from the hornblendes

Table 22. Alkali contents and molecular compositions of hornblendes from basic rocks of the garnet zone in the Grampian Highlands.

	S_1	S_2
Na+K(O=23)	0.443	0.547
Molecular comp.		
Tiam	0.158	0.282
Cum	0.392	——
Ca-cum	——	0.202
St'	0.664	0.376
Gl	0.444	1.436
Ts'	1.232	0.877
Tr	5.108	4.828

Note: The total of all the molecules in each hornblende is taken to be very close to 8. Ca-cum represents $Ca_7Si_8O_{22}(OH)_2$.
S_1: Blue-green hornblende from biotite-epidote-albite-amphibolite from Loch-na-Craige, Argyll. (J. D. H. WISEMAN, 1934).
S_2: Blue-green hornblende from garnet-biotite-epidote-albite-amphibolite from Loch-na-Craige, Argyll. (J. D. H. WISEMAN, 1934).

produced by the central Abukuma regional metamorphism. The alkali contents of these hornblendes from the Dalradian garnet zone are 0.443 and 0.547 in atomic number (O=23), and are higher than that of the hornblende from quartz-free basic rocks of the lowest-grade part of zone B in Abukuma. (The garnet zone is the lowest grade where blue-green hornblende becomes stable instead of actinolite and hence the zone is considered to correspond to the lowest-grade part of zone B where blue-green hornblende becomes predominant instead of actinolite.) The host rocks of these Dalradian hornblendes have normative quartz, and so probably have modal quartz also. It is expected that the alkali contents of the hornblendes in quartz-free rocks associated with the above quartz-bearing ones are still higher.

Comparison of the central Abukuma Plateau with some glaucophanitic metamorphic terrains

In the Bessi district, Sikoku, Japan, is exposed a group of glaucophanitic metamorphic rocks representing conditions ranging from the glaucophane schist facies to the epidote-amphibolite facies (A. MIYASHIRO and S. BANNO, 1958). S. TSUBOI (1936) has reported an analysis of hornblende from a kyanite-epidote-amphibolite of Ipponmatsu in the Bessi district. As shown in column G_1 of Table 23, its alkali content is 0.931 in atomic number (O=23), being much higher than the value for the hornblende from the lowest-grade part of zone B and even higher than the values for the hornblendes from the garnet zone of the Grampian Highlands.

Recently, S. BANNO has analysed several hornblendes from epidote amphibolites in the Bessi district. Through the courtesy of him, I examined these unpublished data, and noticed that these hornblendes also have as high alkali contents as the Ipponmatu hornblende.

Table 23. Alkali contents and molecular compositions of hornblendes from some glaucophanitic metamorphic terrains.

	G_1	G_2	G_3	G_4
Na+K(O=23)	0.931	1.096	0.919	1.106
Molecular comp.				
Tiam	0.078	0.280	0.084	0.304
Cum	0.390	——	0.252	——
Ca-tr	——	0.122	——	0.076
St'	1.416	1.308	1.660	1.820
Ed'	0.223	0.442	——	0.196
Gl	——	——	0.178	——
Ts'	1.802	1.472	1.379	1.567
Tr	4.100	4.376	4.268	4.036

Note: The total of all the molecules in each hornblende is taken to be very close to 8.

G_1: Light bluish green hornblende from kyanite-epidote-amphibolite in Ipponmatu, Bessi district, Sikoku. (S. TSUBOI, 1936)

G_2: Brown hornblende from eclogite in Gertrusk, Sau Alpe, Carinthia. (S. KORITNIG, 1940)

G_3: Bluish green hornblende from amphibolite in New Caledonia. (A. LACROIX, 1942)

G_4: Blue-green hornblende from biotite-bearing chlorite-albite-hornblende-schist from Hochalm-Ankogel Gruppe in the Pennine nappes. (P. PAULITSCH, 1948)

The contents for common hornblendes from other glaucophanitic metamorphic terrains will be examined below. A kind of hornblende called *carinthine* has been known to occur characteristically in rocks from glaucophanitic metamorphic terrains. They are common hornblende characterized by a markedly high alkali content. Columns G_2, G_3, and G_4 of Table 23 show alkali contents of such common hornblendes. Their alkali contents are comparable to or still higher than the value for the Ipponmatu hornblende.

Thus, it is clear that *the alkali content of calciferous amphiboles in quartz-free basic rocks tends to increase with increasing grade of metamorphism, but the actual contents differ in different types of metamorphism. The difference is well represented by different heights of the alkali curves for various districts in Fig. 29.* The alkali contents of hornblendes are low for the central Abukuma regional metamorphism, higher for the Dalradian metamorphism and still higher for the glaucophanitic metamorphism.

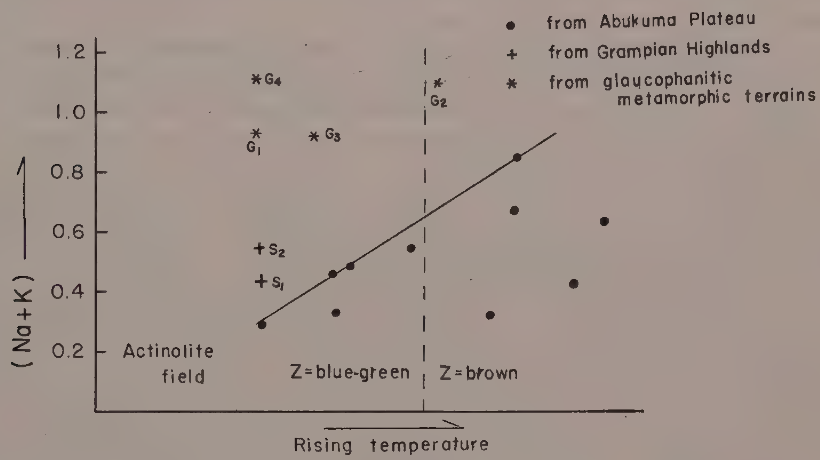

Fig. 29. (Na+K) contents of hornblendes on the anhydrous basis of O=23 from the central Abukuma regional metamorphic terrain in comparison with those from some other districts.

Discussion

What tpyes of substitution are responsible for the differences in the alkali contents of hornblendes in the present case? The molecular compositions of hornblendes from the Grampian Highlands and glaucophanitic metamorphic terrains will be compared below with those from the central Abukuma Plateau.

Glaucophane molecule:

Glaucophane molecule is not present in any hornblende from the central Abukuma Plateau, whereas two hornblendes from the Grampian Highlands and one of four hornblendes from the glaucophanitic metamorphic terrains contain some amount of the molecule. Thus, glaucophane molecule appears to enter more readily into hornblendes under the condition prevailing in the glaucophanitic and Dalradian types of metamorphism than in the central Abukuma regional metamorphism. As before mentioned, edenite and sodatremolite molecules enter into hornblende more readily under higher solid pressures than under lower ones. Glaucophane molecule behaves in a similar way.

$$\underset{\substack{\text{Tremolite}\\(3\times 271\text{ cc})}}{3Ca_2Mg_5Si_8O_{22}(OH)_2} + \underset{\substack{\text{Anorthite}\\(18\times 101\text{ cc})}}{18CaAl_2Si_2O_8} + \underset{\substack{\text{Albite}\\(10\times 102\text{ cc})}}{10NaAlSi_3O_8} + \underset{\text{Water}}{H_2O}$$

$$\rightleftarrows \underset{\substack{\text{Glaucophane}\\(5\times 261\text{ cc})}}{5Na_2Mg_3Al_2Si_8O_{22}(OH)_2} + \underset{\substack{\text{Epidote}\\(12\times 141\text{ cc})}}{12Ca_2Al_3Si_3O_{12}(OH)} + \underset{\substack{\text{Quartz}\\(14\times 22.4\text{ cc})}}{14SiO_2} \quad \ldots\ldots\ldots(6)$$

$$\underset{\substack{\text{Tremolite}\\(271\text{ cc})}}{Ca_2Mg_5Si_8O_{22}(OH)_2} + \underset{\substack{\text{Albite}\\(10\times 101\text{ cc})}}{10NaAlSi_3O_8} + \underset{\substack{\text{Chlorite}\\(2\times 211\text{ cc})}}{2Mg_5Al_2Si_3O_{10}(OH)_8}$$

$$\rightleftarrows \underset{\substack{\text{Glaucophane}\\(5\times 261\text{ cc})}}{5Na_2Mg_3Al_2Si_8O_{22}(OH)_2} + \underset{\substack{\text{Anorthite}\\(2\times 101\text{ cc})}}{2CaAl_2Si_2O_8} + \underset{\text{Water}}{4H_2O} \quad \ldots\ldots\ldots(7)$$

In the above equations, the left-hand side represents common mineral or molecular assemblages of basic rocks in various types of metamorphism. The total volumes of the solid phases of the left-hand sides are 3651 cc and 1713 cc respectively and those of the right-hand sides are 3311 cc and 1507 cc respectively. The total volume of the solid phases in the right-hand side of the two equations is ten or more per cent smaller than that in the left-hand side.

Thus, the glaucophane molecule should tend to increase in common hornblende with increasing solid pressures. Hence, frequent occurrence of glaucophane molecule in hornblende in a metamorphic terrain may be regarded as indicating that the recrystallization took place under high solid pressures.

Edenite and sodatremolite molecules:

Edenite molecule is contained in all the hornblendes from central Abukuma Plateau, whereas it is in smaller amounts or lacking in hornblendes from the Dalradian and glaucophanitic metamorphic terrains. On the other hand, sodatremolite molecule is generally absent in hornblendes of zone B in the central Abukuma plateau, whereas it is contained in large amounts in hornblendes from the Grampian Highlands and in much larger amounts in hornblendes from the glaucophanitic metamorphic terrains.

As shown in equations (2) and (3), the reaction between tremolite and albite results in the formation of edenite molecule in one case and sodatremolite molecule in the other. As seen in equation (3), the formation of sodatremolite from tremolite and albite is accompanied by the liberation of anorthite molecule. The expelled anorthite molecule would further react with tremolite and chlorite to form tschermakite molecule (see equation (4)). Thus, the combined effect of reactions (3) and (4) would decrease largely the total volume of the solid phases of the rock.

From this it is considered that tremolite and albite form sodatremolite molecule rather than edenite molecule under higher solid pressures. Then, it is natural to consider that the rock pressures during metamorphism were high in the glaucophanitic type of metamorphism, lower in the Dalradian type and still lower in the central Abukuma type, because sodatremolite contents of hornblendes decrease generally in this order.

Tschermakite molecule:

Equations (4) and (5) show that the formation of tschermakite molecule would be effectively promoted under higher solid pressures. Actually, the content of the molecule, however, shows no regular variation with the type of metamorphism. It is because some amount of the tschermakite molecule is transformed into pyralspite garnet under high rock pressures, as will be discussed later.

Tremolite molecule:

The amount of the tremolite molecule is large in the hornblendes from the

central Abukuma, smaller in those from the Grampian Highlands and still smaller in those from the glaucophanitic metamorphic terrains. Thus, the amount of the molecule decreases with increasing solid pressure of the formation. This fact is in harmony with the theoretical considerations: As mentioned above, glaucophane, sodatremolite and also tschermakite molecules increase at the expense of tremolite molecule with increasing solid pressure, though some amount of the tschermakite molecule may be transformed into garnet.

Thus, higher rock pressures tend to form calciferous amphiboles with higher alkali contents. The rock pressure prevailing during the regional metamorphism in the central Abukuma Plateau was probably lower than that of the Dalradian metamorphism which the latter in turn was probably lower than that of the glaucophanitic metamorphism.

These conclusions concerning the alkali contents of common hornblende are in harmony with the relations concerning the Mn contents of pyralspite garnets as discussed by A. Miyashiro (1953b).

3. Occurrence of Garnet-Amphibiolite in Relation to Types of Metamorphism

The frequency of occurrence of pyralspite in basic rocks differs in different metamorphic terrains. Ordinary amphibolites in the central Abukuma regional metamorphic terrain do not have pyralspite, whereas pyralspite is one of the commonest constituents in the basic rocks of the epidote-amphibolite and amphibolite facies in the Dalradian and glaucophanitic metamorphic terrains. In the Dalradian series, pyralspite makes the first appearance at the entrance to the garnet zone (or the epidote-amphibolite facies) and is one of the common constituent minerals throughout the garnet, kyanite and sillimanite zones (the latter two zones represent the amphibolite facies). The Mn/Fe^{+2} ratio of the ordinary basic rocks of the central Abukuma Plateau is similar to that of the Grampian Highlands. Probably, the general absence of garnet-amphibolite in the central Abukuma Plateau is not due to a difference in the chemical composition of their host rocks, but is due to a difference in the physical conditions prevailing during metamorphism.

The following equations may explain this situation:

$$\underset{\substack{\text{Tschermakite}\\(5\times 260\text{ cc})}}{5Ca_2Mg_3Al_4Si_6O_{22}(OH)_2} \rightleftarrows \underset{\substack{\text{Almandine}\\(5\times 113\text{cc})}}{5Mg_3Al_2Si_3O_{12}} + \underset{\substack{\text{Grandite}\\(2\times 126\text{ cc})}}{2Ca_3Al_2Si_3O_{12}} + \underset{\substack{\text{Quartz}\\(3\times 22.4\text{ cc})}}{3SiO_2} + \underset{\substack{\text{Epidote}\\(2\times 141\text{ cc})}}{2Ca_2Al_3Si_3O_{12}(OH)} + \underset{\text{Water}}{4H_2O} \quad (8)$$

$$\underset{\substack{\text{Tschermakite}\\(2\times 260\text{ cc})}}{2Ca_2Mg_3Al_4Si_6O_{22}(OH)_2} \rightleftarrows \underset{\substack{\text{Almandine}\\(2\times 113\text{ cc})}}{2Mg_3Al_2Si_3O_{12}} + \underset{\substack{\text{Grandite}\\(126\text{ cc})}}{Ca_3Al_2Si_3O_{12}} + \underset{\substack{\text{Anorthite}\\(101\text{ cc})}}{CaAl_2Si_2O_8} + \underset{\substack{\text{Quartz}\\(22.4\text{ cc})}}{SiO_2} + \underset{\text{Water}}{2H_2O} \quad (9)$$

$$\underset{\substack{\text{Tschermakite}\\(2\times 260\text{ cc})}}{2Ca_2Mg_3Al_4Si_6O_{22}(OH)_2} + \underset{\substack{\text{Albite}\\(2\times 102\text{ cc})}}{2NaAlSi_3O_8} \rightleftarrows \underset{\substack{\text{Glaucophane}\\(261\text{ cc})}}{Na_2Mg_3Al_2Si_8O_{22}(OH)_2} + \underset{\substack{\text{Almandine}\\(113\text{ cc})}}{Mg_3Al_2Si_3O_{12}} + \underset{\substack{\text{Epidote}\\(2\times 141\text{ cc})}}{2Ca_2Al_3Si_3O_{12}(OH)} + \underset{\substack{\text{Quartz}\\(22.4\text{ cc})}}{SiO_2} \quad (10)$$

In these equations, the total volumes of the solid phases of the left-hand sides are 1300 cc, 520 cc, and 724 cc respectively, and those of the right-hand sides are 1164 cc, 475 cc, and 680 cc respectively, the solid phases of the right-hand sides having smaller total volume than those of the left-hand ones. Thus, under higher rock pressures, these equations go to the right, resulting in the formation of garnet.

J. D. H. WISEMAN (1934) analysed a pyralspite from epidote-garnet-amphibolite in the garnet zone of the Dalradian series. (The associated hornblende was also analysed by him as shown in column S_2 of Table 22.) The analysed pyralspite contains Ca atoms half as many as $Fe^{+2}+Mg+Mn$ and is similar in composition to tschermakite. In order to show the close compositional relation between the two, the pyralspite is plotted on an ACF diagram along with the various main constituting molecules of the calciferous amphiboles with the result shown in Fig. 30. The pyralspite falls on nearly the same position as tschermakite molecule. In this case, therefore, the pyralspite and grandite molecules of the above

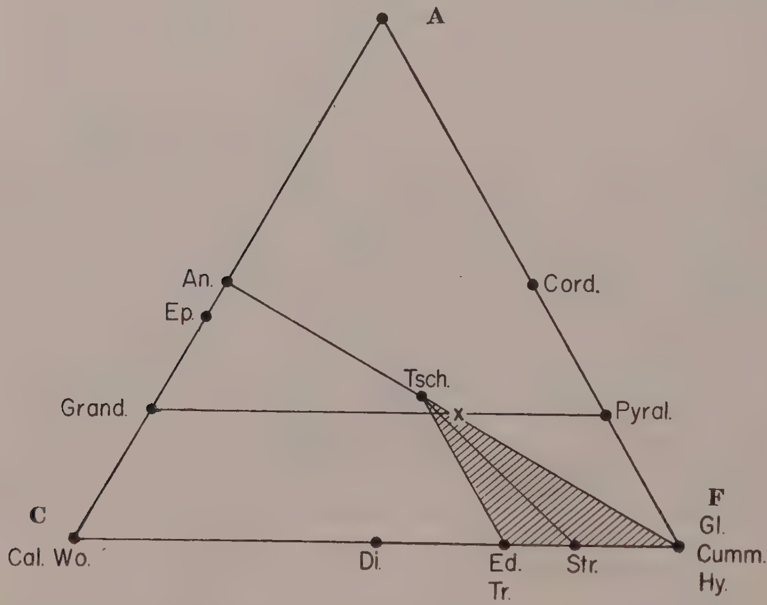

Fig. 30. Compositions, plotted on the ACF diagram, of some minerals and the main component molecules of hornblende. The cross represents the garnet from epidote-amphibolite W_2 of the Grampian Highlands (WISEMAN, 1934). The diagram shows that tschermakite is very similar to garnet in chemical composition.
Grand.=grandite, Pyral=pyralspite, Tsch.=tschermakite, Str.=soda-tremolite, Ed.=edenite, Tr.=tremolite, Gl.=glaucophane, Cumm.=cummingtonite, Hy.=orthopyroxene.

equations may be united to form a single phase of the mineral pyralspite. Pyralspites from basic rocks in the glaucophanitic metamorphic terrains also usually contain considerable amounts of Ca. Thus, roughly speaking, Ca-rich pyralspite may be regarded as having a polymorphic relation to tschermakite, the former being a high-solid pressure form of the latter.

The Mn content of calciferous amphibole merits attension in relation to

types of metamorphism. In Table 24, the MnO contents of common hornblendes from the central Abukuma Plateau are compared with those from the Dalradian and glaucophanitic metamorphic terrains. The contents are relatively high in the central Abukuma regional metamorphism and lower in the Dalradian and glaucophanitic metamorphism, although the Mn contents of the host rocks are similar. Thus, the content of common hornblende decreases with increasing rock pressure of their formation.

Table 24. The MnO contents of common hornblendes from basic rocks in various metamorphic terrains.

Localities	Zone	MnO in Wt %	References
The central Abukuma	Zone C	0.21 0.29 0.30 0.32 0.43	Present paper
	Zone B	0.33 0.37 0.41 0.69	Present paper
The Grampian Highlands	Garnet zone	0.20 0.25	J. D. H. Wiseman (1934)
Glaucophanitic metamorphic terrains	Epidote-amh'te facies	0.004	S. Koritnig (1940)
		0.11	A. Lacroix (1942)
		0.18	S. Tsuboi (1936)
		0.20	P. Paulitsch (1948)

A. Miyasiro (1958) noticed that the MnO content of biotite from psammitic and pelitic metamorphic rocks are higher in the central Abukuma type of metamorphism than in the Dalradian metamorphism. Probably, higher solid presrure promotes the formation of pyralspite, which in turn tends to take more Mn away from biotite as well as from hornblende, resulting in the decrease of the Mn contents in biotite and hornblende.

4. Occurrence of Cummingtonite in Relation to Type of Metamorphism

Cummingtonite occurs very frequently in ordinary basic rocks of the central Abukuma regional metamorphic terrain and also of the Iritōno contact-metamorphic aureole. The mineral has also been reported from the Orijärvi and some other metamorphic districts characterized by the occurrence of andalusite in pelitic rocks of appropriate compositions. On the other hand, cummingtonite does not occur, so far as I know, in ordinary basic rocks of the Grampian Highlands and glaucophanitic metamorphic terrains. Then, we may consider that the metamorphisms producing andalusite tend to produce cummingtonite in ordinary basic rocks, whereas those producing kyanite tend not to produce cummingtonite. The reason is given below:

$$14CaAl_2Si_2O_8 + 3Mg_7Si_8O_{22}(OH)_2 + 4H_2O \rightleftarrows 7Ca_2Mg_3Al_4Si_6O_{22}(OH)_2 + 10SiO_2$$
Anorthite (14 × 101 cc) | Cummingtonite (3 × 269 cc) | Water | Tschermakite (7 × 260cc) | Quartz (10 × 22.4 cc)

$$\rightleftarrows 7/5\{5Mg_3Al_2Si_3O_{12} + 2Ca_3Al_2Si_3O_{12} + 2Ca_2Al_3Si_3O_{12}(OH) + 3SiO_2 + 4H_2O\} \ldots\ldots\ldots (11)$$
7/5{ Almandine (5 × 113 cc) | Grandite (2 × 126 cc) | Epidote (2 × 141 cc) | Quartz (3 × 22.4 cc) | Water}

As shown in this equation, the assemblage cummingtonite-anorthite is equivalent in chemical composition of solid phases to the assemblage tschermakite-quartz and also equivalent to the assemblage garnet-epidote-quartz. The total volume of the solid phases is 2221 cc in the first assemblage involving cummingtonite, 2044 cc in the second one involving tschermakite, and 1621 cc in the last one involving garnet. Then it is clear that the occurrence of cummingtonite characterizes the metamorphisms under low rock pressures, whereas as mentioned previously, the occurrence of garnet characterizes the metamorphisms under high solid pressures. The metamorphism that produces cummingtonite as a common constituent of basic rocks does not produce garnet-amphibolite, so far as I am aware.

The cummingtonite molecule of common hornblende is also expected to behave in the same way as the mineral cummingtonite. Cummingtonite molecule is contained in considerable amounts in all the hornblendes from the central Abukuma, whereas it is in smaller amounts, if present, in the Dalradian and glaucophanitic metamorphic terrains.

As mentioned before, under favourable conditions, the tschermakite molecule transforms into cummingtonite and anorthite with rising temperature. The transformation temperature should become lower under lower solid pressures. In the central Abukuma regional metamorphism, a fairly long interval in grade exists between the appearance of cummingtonite and that of orthopyroxene. Under higher solid pressures, the appearance of cummingtonite would be delayed till orthopyroxene makes the first appearance, thus leading to the lack of cummingtonite throughout the metamorphic terrain.

5. Status of the Epidote-Amphibolite Facies

According to F. J. TURNER and J. VERHOOGEN (1951) and H. RAMBERG (1944), the critical mineral assemblage for the epidote-amphibolite facies is albite (or oligioclase)-epidote-common hornblende. This facies is distinguished from the lower facies by the stable presence of common holnblende. The amphibiolite facies is defined as the P–T range for which the assemblage common hornblende-andesine (or more calcic plagioclase) is stable. Then, it follows that the amphibolite facies is distinguished from the epidote-amphibolite facies by the presence of andesine or more calcic plagioclase in ordinary basic rocks.

The appearance of common hornblende marks the entrance from the actinolite-greenschist facies to the epidote-amphibolite facies. As mentioned before, under higher rock pressures, the first appearance of common hornblende becomes lower in grade. Therefore, the greenschist facies is on the lower-temperature and lower-solid pressure side of the boundary to the epidote-amphibolite facies on the P_{rock}–T field.

Under higher rock pressures, the stability range of epidote extends toward higher grades and consequently plagioclase remains sodic till higher grades than

under lower solid pressures. Therefore, the amphibolite facies is on higher-temperature and lower solid pressure side of the boundary to the epidote-amphibolite facies.

From these considerations the development of the epidote-amphibolite facies appears to be controlled by the magnitude of the solid pressure prevailing. This facies is actually confined to the metamorphism under high solid pressures. The assemblage albite (or oligoclase)-epidote-common hornblende develops generally extensively in the Dalradian and glaucophanitic metamorphic terrains, whereas it is practically lacking in the central Abukuma regional metamorphic terrain. In the Dalradian series, the plagioclase in the grade where common hornblende first appears is albite and ramains to be albite in most of the garnet zone and epidote is common up to the kyanite zone. In glaucophanitic metamorphic terrain, the plagioclase is generally albite and rarely oligoclase. On the other hand, in the central Abukuma regional metamorphism, the plagioclase is not albite, but oligoclase in the grade where hornblende makes its first appearance, and plagioclase becomes more calcic very rapidly up to labradorite composition with advancing metamorphism. Thus the albite (or oligoclase)-epidote-common hornblende assemblage is practically lacking in that metamorphism. In the contact-metamorphic rock series of the Iritōno district, the above critical assemblage of the epidote-amphibolite facies is utterly lacking and moreover epidote is probably unstable even in the basic rocks of the lowest grade (zone A′).

Fig. 31 gives a schematic diagram showing the relation between the epidote-amphibotite facies and other metamorphic facies.

In this paper, the effects of water pressure on the reactions concerned have not been taken into consideration. A variation in water pressure should promote some reactions and obstrust others. However, practically all the mineralgical characters of the various metamorphisms have been sufficiently explained by the effects of differences in solid pressures, without considering those of water pressure. This fact suggests that the controlling effect of water pressure on the type of metamorphism is not so large.

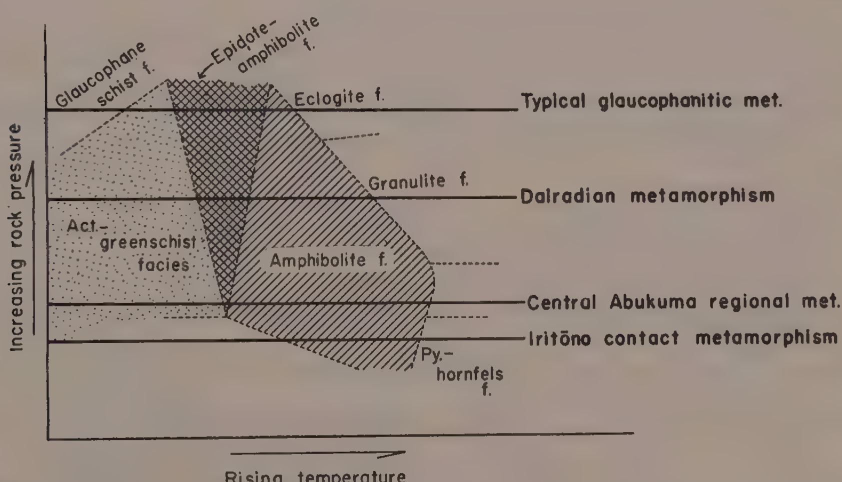

Fig. 31. Tentative diagram showing the P-T fields of the epidote-amphibolite facies and some other metamorphic facies. Dotted lines represent a facies boundary.

ACKNOWLEDGEMENTS

The present study was carried out in the Graduate School of the University of Tokyo for partial fulfillment of the requirements of the degree of doctor. I am greatly indebted to Prof. Hisashi KUNO and Asst. Prof. Akiho MIYASHIRO for their valuable suggestions and advices, and also for critical reading of the manuscript. I wish to express my thanks to Prof. I. IWASAKI, Dr. T. KATSURA and Mr. H. HARAMURA of the Tokyo Institute of Technology for chemical analyses used in the present study. Thanks are also due to other members of the Geological Institute, University of Tokyo for providing facilities during the course of this study.

A part of the expense of this study was defrayed by the Grant in Aid for Scientific Researches from the Ministry of Education of Japan, which is also appreciated.

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REGIONAL METAMORPHISM OF THE GOSAISYO-TAKANUKI DISTRICT IN THE CENTRAL ABUKUMA PLATEAU

By

Akiho MIYASHIRO

CONTENTS

ABSTRACT

Regional-metamorphic rocks are widely exposed in the Gosaisyo-Takanuki district. The metamorphism is generally considered to have taken place in late Paleozoic or early Mesozoic time. It was accompanied by intrusion of gabbroic and granodioritic masses.

The *metamorphic grade* increases westward. The westward increase of metamorphic grade is on a regional scale and the individual plutonic masses had only slight additional effects on it. Probably, the distribution of metamorphic grades was mainly controlled by the regional uprise of isogeothermal surfaces within the geosynclinal pile, though the individual plutonic masses made slight modifications to it.

The metamorphic terrain is divided into *three zones*, *A*, *B and C*, on the basis of progressive change in calciferous amphiboles in response to rising temperature. Zone A is characterized by actinotite, zone B is characterized by "blue-green common hornblende", in which the axial color of Z is bluish green or greenish blue. Zone C is characterized by common hornblende without bluish tinge, in which the axial color of Z is green, yellow-brownish green, or brownish yellow.

The most common rocks of basic compositions are chlorite-epidote-actinolite-schist in zone A, and hornblende-plagioclase-schist or amphibolite in zones B and C. The most common rocks of pelitic type are graphite-chlorite-biotite-quartz-schist in zone A, biotite-plagioclase-quartz-schist in zone B, and biotite-K-felspar-plagioclase-quartz-gneiss with some pyralspite and/or sillimanite in zone C.

Andalusite and cordierite occur rarely in pelitic rocks of zones B and C. The inversion point from andalusite to sillimanite was in the lower-grade part of zone C. Muscovite is decomposed into sillimanite and K-felspar probably in the middle of zone C. (See Fig. 4.) In calcic metamorphic rocks, clinopyroxene of the diopside-hedenbergite series begins to occur in the lower-grade part of zone B, and grandite begins to occur in the middle of the same zone.

The *plagioclase* is albite and oligoclase in zone A, and oligoclase, andesine and labradorite in zones B and C. In the plagioclase series, there may exist a miscibility gap in the composition range of 40–50% in a certain part of zone B. The

increase of the An content of plagioclase with increasing grade is more rapid in the present metamorphism than in the Dalradian of the Grampian Highlands of Scotland.

The Mn contents of *pyralspite garnets* in ordinary pelitic metamophic rocks decrease regularly with increasing grade. The Mn contents are much higher in the present metamorphism than in the Dalradian one. Pyralspite did not form in ordinary basic rocks in the present metamorphism.

The Mn contents of *biotites* in ordinary pelitic metamorphic rocks also tend to decrease with increasing grade. The Mn contents are higher in the present metamorphim than in the Dalradian one.

The composition range of *muscovite* dwindles with the passage from zone B to C, and probably vanishes in the higher-grade part of zone C.

Zone A belongs to the actinolite-greenschist facies, and zones B and C belong to the amphibolite facies. Thus, *the actinolite-greenschist facies grades directly into the amphibolite facies*. The epidote-amphibolite facies, characterized by the assemblage albite (or oligoclase)-epidote-common hornblende, is practically lacking in the present metamorphism owing to very rapid increase of the An content with increasing grade.

The above features indicate that the regional metamorphism of the present district took place under lower solid pressures than that of the Dalradian series. Metamorphisms identical and similar in mineralogical characters to that of the present district is called the *metamorphisms of the central Abukuma type*. They are well-developed in Japan and Australia. Probably, the metamorphisms of the central Abukuma type are widespread in the world to a similar extent as those of the Dalradian type.

The biotites of the Gosaisyo-Takanuki district tend to have higher $Fe^{+3}/(Fe^{+2}+Fe^{+3})$ ratios than those of the Dalradian series. It may be due to higher water pressures that prevailed during the formaton of the former.

The K contents of the metamorphic rocks increase generally with increasing grade, probably as a result of the introduction of K from outside. Monovalent atoms such as K could diffuse probably rather freely through the rocks during metamorphism. Atoms with higher valencies, on the other hand, had very narrow scopes of diffusion. However, such atoms may have migrated rather freely through bodily flow of aqueous solutions and magmatic melts.

I. INTRODUCTION

Various schistose metamorphic rocks are exposed in a district, about 30 km. in width from east to west, around Gosaisyo and Takanuki in the central part of the Abukuma Plateau (latitude 36°55′–37°10′ N, longitude 140°30–50′ E). The metamorphism is of regional type, and the metamorphic grade increases generally westward.

Gosaisyo (Gosaisho) is a small mountain having a shrine on the top and situated in the eastern part of the district. Takanuki (Takenuki) is a hamlet in the middle of the western part. These names became famous among the Japanese geologists through the pioneer work of B. Koto (1892). K. Sugi (1935) described some general characters of the metamorphic rocks. M. Gorai (1944) and I. Watanabe et. al. (1955) cast much light on the igneous activity of the district.

I have studied the metamorphic rocks of the district since 1947, and published two preliminary notes (Miyashiro, 1953a, 1953b). In the present paper, I describe

the metamorphism in greater detail with special reference to the metamorphic facies developed.

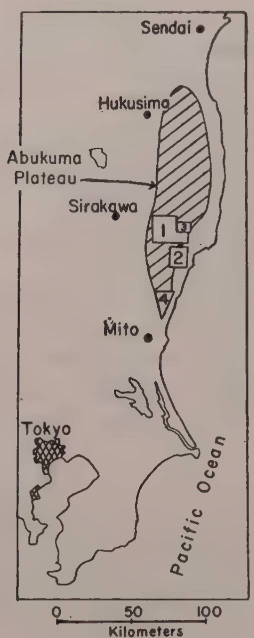

Fig. 1. Location of the Gosaisyo-Takanuki district (1), the Nakoso district (2), and the Iritōno district (3) in the central part of the Abukuma Plateau, and the Hitati district (4) in the southern part.

The study of progressive regional metamorphism has been so far made mainly in the Grampian Highlands of Scotland, in Norway and in the northeastern part of the United States of America, and the results have afforded the most important basis for metamorphic petrology. This situation has induced many petrologists to assume implicitly or explicitly that the metamorphisms of these countries are typical of regional metamorphism in general. This assumption, however, is not justified. The regional metamorphism of the Gosaisyo-Takanuki district differs greatly in character from those of the above-cited countries, and the regional metamorphisms similar to it appear to have taken place widely not only in different parts of Japan but also in other parts of the world. This type of regional metamorphism would not be inferior in geological significance to the type represented by the metamorphism of the Grampian Highlands. I wish to establish a progressive series of mineral facies for this undeservedly neglected type.

Recently, Fumiko SHIDÔ of our University studied the plutonic and metamorphic rocks of the Nakoso district that is situated to the south of the Gosaisyo-Takanuki (Fig. 1). These metamorphic rocks of the Nakoso district represent the southern extension of the metamorphic complex of the Gosaisyo-Takanuki district, and develop a practically identical series of mineral facies. The spatial distribution of metamorphic grades is more regular and on a much smaller scale in the Nakoso district than in the Gosaisyo-Takanuki. Her paper (SHIDÔ, 1958) that is to be published simultaneously with this paper will be referred to repeatedly.

II. GEOLOGY

1. Preliminary Statement

The greater part of the Abukuma Plateau is made up by regional metamorphic rocks (mainly schists and gneisses) and plutonic rocks (gabbro, diorite, granodiorite and granite). Along the eastern border of the Plateau, Mesozoic sediments are exposed in two districts, Soma and Hutaba. The Plateau is surrounded mostly by Tertiary and Quaternary sediments and volcanics.

Metamorphic rocks are widely exposed in the Gosaisyo-Takanuki district in the central part of the Plateau and in the Hitati (Hitachi) district in the southern part (Figs. 1 and 2). M. WATANABE (1920) discovered lower Carboniferous fossils in limestones associated with the low-grade schists of the Hitati district. Therefore, a part, at least, of the metamorphic rocks of the Hitati district was derived

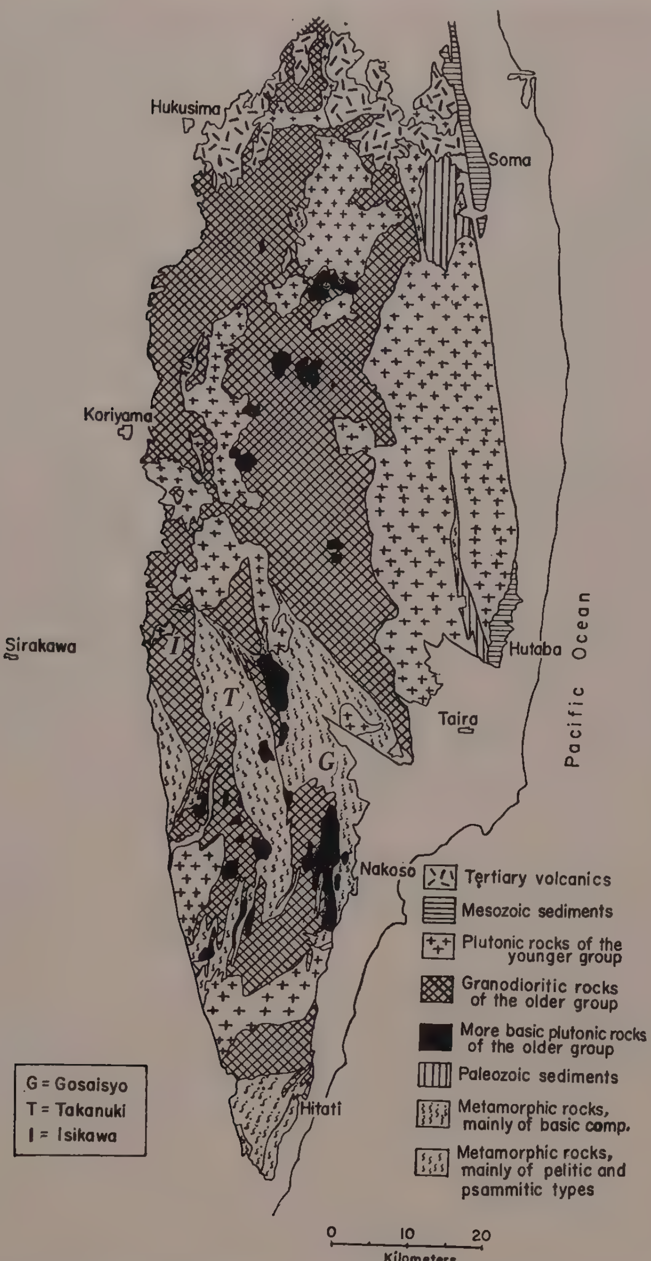

Fig. 2. Geologic sketch map of the Abukuma Plateau, based on geologic survey by M. GORAI, I. WATANABE and many others. The white area surrounding the Plateau is mostly covered by sediments and volcanics of Tertiary and Pleistocene ages.

from Carboniferous sediments, and the metamorphism should be Carboniferous or later.

The metamorphic terrains of the Hitati and Gosaisyo-Takanuki districts, however, are separated from each other by plutonic masses. No fossil has been

found in the latter district. Therefore, the age of sedimentation of the original rocks in the Gosaisyo-Takanuki district is not clear. The oldest dated rocks in the Abukuma Plateau are Devonian sediments in the northern part. Then, the original rocks of the Gosaisyo-Takanuki district also may be Upper Paleozoic.

2. Plutonic Rocks of the Older Group and Related Regional Metamorphism

WATANABE et al. (1955) divided the plutonic rocks of the Abukuma Plateau into two groups: *older* and *younger**. The activity of the older group is related to the regional metamorphism of the Hitati district and hence was in Carboniferous or later. On the other hand, WATANABE et al. considered it to be pre-midde Jurassic, because pebbles that appear to have been derived from plutonic masses of the older group were found in the middle Jurassic sediments of the Soma district.

The plutonic masses genetically associated with the regional metamorphic rocks of the Gosaisyo-Takanuki district belong to the older group. Then, the regional metamorphism of the Gosaisyo-Takanuki district also took place probably at some time from Carboniferous to Jurassic.

The plutonic activity of the older group is made up of the intrusion of hornblende-gabbro commonly with small amount(s) of cummingtonite, hypersthene and/or augite, and that of a larger amount of biotite-granodiorite. Usually they form composite masses. The gabbroic rocks have no noticeable preferred orientation, whereas the granodiorite usually has remarkable parallel structure, generally conformable to the schistosity of the surrounding metamorphic rocks.

GORAI (1944) named the plutonic masses of the older group in the Gosaisyo-Takanuki district " Tabito ", " Miyamoto ", " Samegawa ", and " Isikawa " composite masses, as shown in Fig. 3 (p. 228). In the first two composite masses, the

Table 1. Granodioritic rocks of the older group.

No.	1	2	3
SiO_2	59.40	61.02	62.52
Al_2O_3	19.20	18.97	18.50
TiO_2	0.98	0.94	0.56
Fe_2O_3	1.42	1.11	1.64
FeO	4.14	3.77	3.23
MnO	n.d.	n.d.	0.03
MgO	3.08	2.86	1.51
CaO	5.14	5.00	4.36
Na_2O	4.01	2.51	3.56
K_2O	1.31	2.67	2.20
H_2O_+	1.21	1.31	1.30
H_2O_-	0.40	0.34	0.49
P_2O_5	0.04	0.04	0.05
	100.33	100.54	99.95

No. 1: Schistose granodiorite from Tokura.
No. 2: Schistose granodiorite from Sekihata.
No. 3: Schistose granodiorite from Miyakozi.
Note—The analyses were made by H. SHIBATA (SHIBATA, OKADA and HARA, 1954). For more analyses with detailed descriptions see SHIDÔ (1958). See Fig. 5 also.

* The older group corresponds to the second phase intrusives and the younger group to the third phase intrusives of GORAI (1944).

eastern half, which is generally in contact with basic metamorphic rocks, is mainly gabbroic or dioritic, whereas the western half, which is generally in contact with pelitic an and psammitic metamorphic rocks, is mainly granodioritic. The remaining two composite masses, which are generally surrounded by pelitic and psammitic metamorphic rocks, are mainly composed of granodiorite. This fact suggests that the formation of the gabbroic rocks may be related to basic metamorphic rocks of the district in some way.

Three chemical analyses of granodioritic rocks of the older group are shown in Table 1. The compositional variation of plutonic rocks in the MgO–($FeO+Fe_2O_3$)–(Na_2O+K_2O) diagram is shown in Fig. 5 (p. 239).

3. Plutonic Rocks of the Younger Group and Related Contact Metamorphism

The activity of the younger group of plutonic rocks is probably later than the deposition of the Jurassic sediments in the Soma district, and earlier than that of the Upper Cretaceous sediments in the Hutaba district. The plutonic rocks of this group are poor in or devoid of parallel structures, and produced hornfelses in the contact aureole. Shidô (1958) described a progressive series of hornfelses in the aureole around a composite mass of the younger group in the Iritōno district (Fig. 1).

4. Kinds and Structures of the Regional-Metamorphic Rocks

In the eatern half of the Gosaisyo-Takanuki district, most of the regional-metamorphic rocks are basic in composition and were derived probably from tuff and other pyroclastic material which were interbedded with much smaller amounts of pelitic and psammitic sediments. On the other hand, in the western half of the district, most of the regional-metamorphic rocks were derived from pelitic, psammitic and highly siliceous sediments, being acompanied by much smaller amounts of calcic and basic materials.

Basic sills and dykes were found at places to have intruded these rocks and have been metamorphosed in the same grade as the country rocks. Ultrabasic rocks are very rare and they seem to have been emplaced before and/or during the metamorphism.

In most of the metamorphic rocks, the schistosity plane is parallel to the original bedding. In the area to the east of the Miyamoto composite mass, the schistosity planes strike generally north-south or N 10°W with nearly vertical to 80°W dips. The lineation plunges 0°–30° to the north in the schistosity plane. Small folds, usually isoclinal, are abundant and the fold axes are parallel to the lineation.

In the area to the west of the Miyamoto composite mass, some recent investigators including K. Yagi and I. Watanabe have found that the schistosity planes strike concentrically around the Samegawa composite mass with dips of 30°–70° away from the mass.

III. ZONAL MAPPING

1. Preliminary Statement

The present regional-metamorphic terrain can be divided into zones representing progressive mineralogical changes in response to rising temperature. The zonal mapping may be made in various different ways.

I have ever divided the terrain into four zones, I, II, III and IV, in the study of the progressive metamorphism of the calcic (Ca-rich) rocks (Miyashiro,

1953a). These zones, in the order of increasing metamorphic grade, are as follows.

Zone I: In this zone, the temperature of metamorphism was so low that neither clinopyroxene nor grandite (lime-garnet) was formed. Instead the assemblage calcite-calciferous amphibole-quartz or calcite-epidote-quartz occurs respectively.

Zone II: This zone is characterized by the entrance of clinopyroxene of the diopside-hedenbergite series and grandite in calcic rocks. These minerals persist into the succeeding zones.

Zone III: This zone is characterized by the disappearance of epidote.

Zone IV: This zone is characterized by the entrance of wollastonite.

Later it was found, however, that clinopyroxene begins to occur at a somewhat lower grade than grandite, and that the definition of zone III is inconvenient, because epidote is readily formed through retrogressive reactions even in zones III and IV. Moreover, the temperatures of reactions characterizing these zones depend on the CO_2 pressure existing, which was probably different in different parts of the district. Then, this scheme of zonal mapping is not adopted in this paper.

I have shown that the Mn contents of pyralspite garnets in ordinary pelitic metamorphic rocks decrease regularly with increasing grade of metamorphism in this district (MIYASHIRO, 1953b). Then, the compositions of pyralspites may be used as a grade-indicator for zonal mapping if necessary.* This scheme of mapping, however, is not adopted in this paper, because precise zonal mapping on this scheme requires a too large number of chemical analyses of pyralspites.

2. Scheme of Zonal Mapping Adopted in this Paper

In this district, the nature of calciferous amphibole in basic metamorphic rocks varies in a regular way with increasing grade of metamorphism. This variation is most clearly revealed in the axial color of Z. Therefore, zonal mapping can be made in terms of the axial color of Z in the calciferous amphiboles. As basic metamorphic rocks are widespread, this type of zonal mapping is the most convenient for the present district and is adopted in this paper. Thus, we have the following metamorphic zones in the order of increasing grade.

Zone A: *In this zone the characteristic calciferous amphibole is actinolite.* The axial color of Z is colorless or very pale green. In the higher-grade part of this zone, a small amount of common hornblende usually occurs in association with actinolite. The axial color of Z in the common hornblende ranges from bluish green to greenish blue, and such hornblende will be called *blue-green common hornblende* (or blue-green hornblende) in this paper.

Zone B: With increasing grade, the amount of blue-green common hornblende increases and that of actinolite decreases. The boundary between zones A and B is drawn where blue-green common hornblende becomes as abundant as actinolite. Then, *blue-green common hornblende is the predominant calciferous amphibole in the lower-grade of zone B and the only one in the higher-grade part of the zone.*

Zone C: This zone is characterized by common hornblende without bluish tinge, in which the axial color of Z is green, yellow-brownish green, or brownish

* Recently HEIER (1956) came to a conclusion in agreement with me as regards the possibility of zonal work on the basis of the compositions of pyralspites.

yellow. In other words, *the entrance to zone C is marked by the vanishing of bluish tinge in Z of common hornblende formed.*

The three kinds of calciferous amphiboles have distinctive optical and chemical characteristics as will be shown on later pages. It has not been clarified yet whether the color variation from blue-green hornblende of zone B to hornblende without bluish tinge of zone C is a results of chemical changes (such as an increase of Ti content) in response to rising temperature or a result of some structural changes. Someone would consider that the axial color of calciferous amphiboles are inappropriate as the basis of zonal work so far as the cause of the color variation has not been clarified.

Nevertheless, this scheme has been adopted for the following two reasons:

(1) The metamorphic grades and zones based on the variation of the axial color have been proved to be consistent with the grades measured with all the other mineralogical changes.

(2) The metamorphic grades and zones on this scheme can be readily correlated with those on any other schemes. Refer to Fig. 4. For example, epidote in basic metamorphic rocks disappears generally in the middle of zone B, and andalusite in pelitic metamorphic rocks is transformed into sillimanite in the lower-grade part of zone C. Zone A corresponds to the lower-grade part of zone I for calcic rocks, zone B corresponds to the higher-grade part of zone I and all the zone II, and zone C corresponds to zones III and IV.

3. Distribution of Metamorphic Zones and their Relation to Plutonic Masses

The distribution of the metamorphic zones is shown in Fig. 3. The metamorphic grade inreases westward.

Plutonic masses of the older group, the intrusion of which was roughly synchronous with the regional metamorphism, are abundant not only in the western part of the district but also in the eastern part, as is clear from Figs. 2 and 3. Then, the westward increase of the metamorphic grade is not due to special abundance of plutonic masses in the west.

The westward increase of the metamorphic grade is on a regional scale, and the individual plutonic masses had only slight additional effects on it. Probably, the distribution of metamorphic grade was mainly controlled by the regional uprise of isogeothermal surfaces within the geosynclinal pile, and the individual plutonic masses made only slight modifications to it.

Probably, the regional uprise of isogeothermal surfaces was a result of the upward transfer of heat from the depth, partly due to conduction through the crust and partly due to flow of high-temperature materials (water and others).

In most of the eastern part of the district, metamorphic rocks in contact with plutonic masses belong to zone B. Most, at least, of the rocks in contact with the western margin of the Miyamoto composite mass also belong to zone B. However, very narrow areas, less than a few tens of meters wide, in contact with some parts of the eastern margin of the Miyamoto composite mass belong to zone C. (As these areas are very narrow, they are not shown in Fig. 3.) Probably, this indicates a difference in contact effects between the western part and the eastern part of the composites mass.* The eastern part is composed

* I have ever stated that a belt in contact with the western margin of the Miyamoto composite mass is higher in metamorphic grade than the area in the further west (MIYASHIRO, 1953a). The statement was mainly based on the occurrence of wollastonite in the belt. The formation of wollastonite, however, is probably too greatly influenced by the local variation of CO_2 pressure to be used as a geologic thermometer. Probably, such a higher grade belt does not exist.

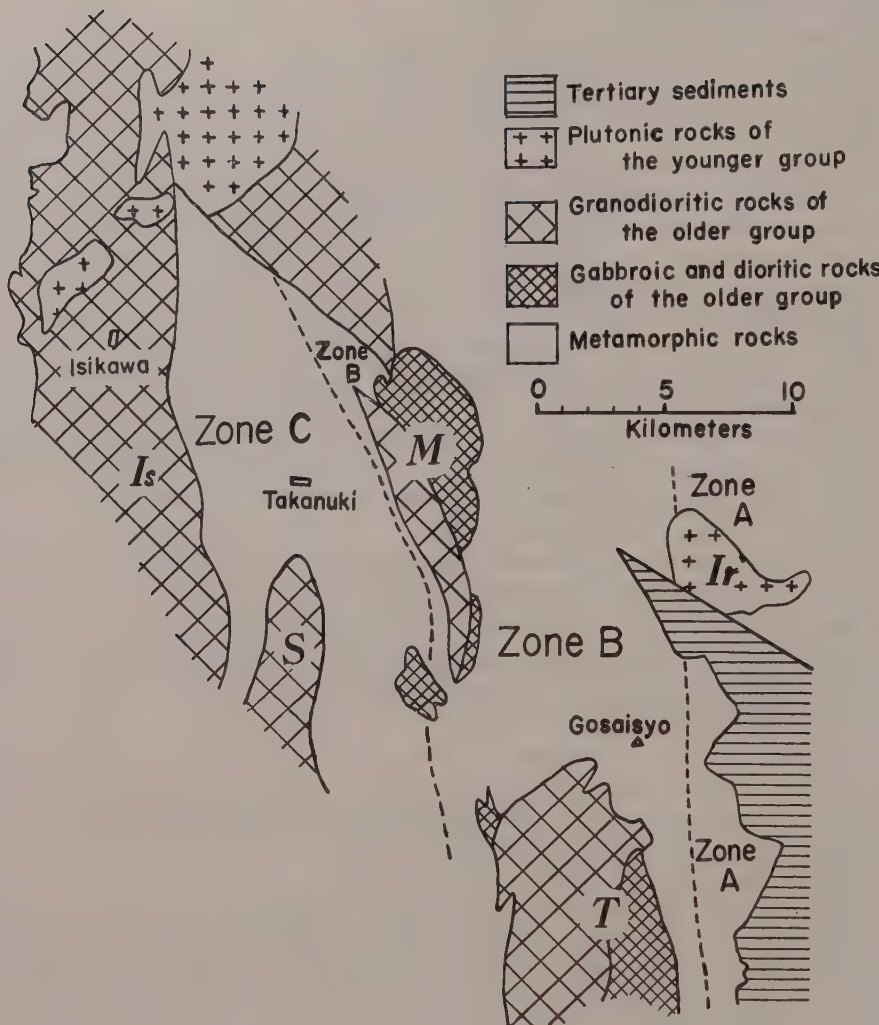

Fig. 3. Regional-metamorphic zones in the Gosaisyo-Takanuki district. The zone boundaries are indicated by dotted lines. T=Tabito composite mass, M=Miyamoto composite mass, S=Samegawa composite mass, and Is=Isikawa composite mass. (Ir=Iritōno composite mass, which belongs to the younger group. The contact aureoles around the plutonic masses of the younger group are not shown.)

of gabbroic and dioritic rocks, which were probably higher in temperature of intrusion than the granodioritic rocks of the western part.*

The boundary between zones A and B and that between zones B and C are both roughly parallel to the general trend of the schistosity in the areas concerned.

* In the Nakoso district, SHIDÔ (1958) shows that the metamorphism is generally in the grades of zones A and B, but increases to the grades of zone C and even still higher (called zone D) locally around the dioritic and gabbroic masses. This also indicates that the contact effects of dioritic and gabbroic masses were of higher-temperature type than those of granodioritic masses.

On the east, the metamorphic rocks of zone A are unconformably covered by Tertiary sediments. Then, the gradation from unmetamorphosed to metamorphosed area cannot be observed.

4. Cursory Survey of Progressive Mineralogical and Textural Changes

The mineralogical variations with increasing grade are summarized in Fig. 4. The most common rocks of basic compositions are chlorite-epidote-actinolite-schist in zone A, and hornblende-plagioclase-schist or amphibolite in zones B and C. The most common rocks of pelitic type are graphite-chlorite-biotite-quartz-schist in zone A, biotite-plagioclase-quartz-schist with or without muscovite in zone B, and biotite-K-felspar-plagioclase-quartz-gneiss with some pyralspite and/or sillimanite in zone C. Much more detailed descriptions will be given later.

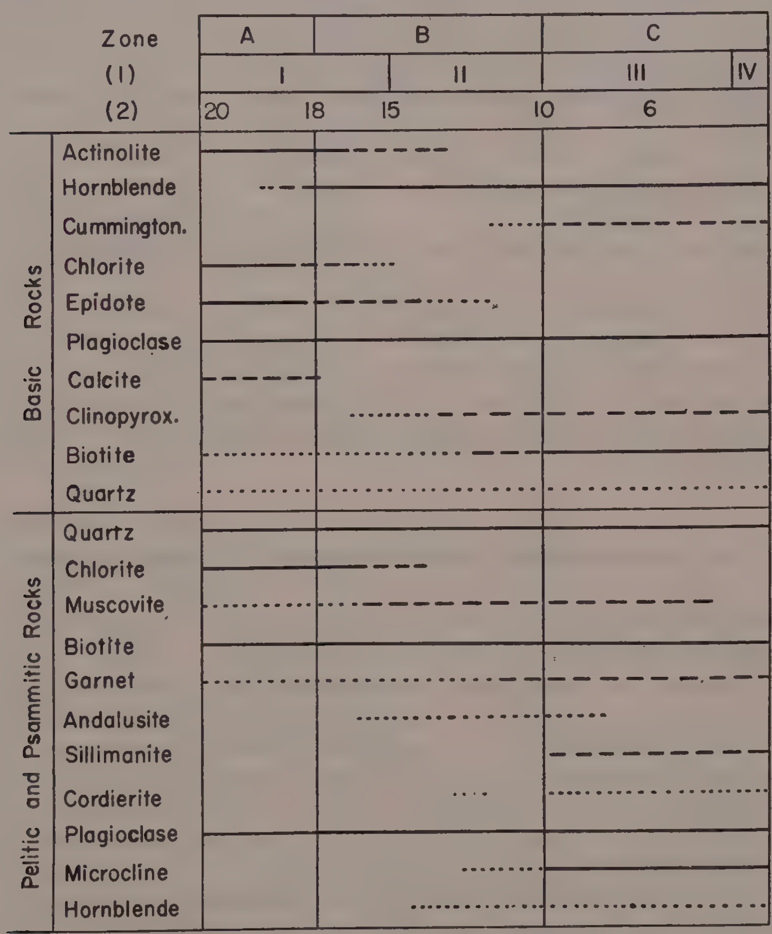

Fig. 4. Mineralogical variations with increasing grade of metamorphism in basic, pelitic and psammitic rocks of the Gosaisyo-Takanuki district. Line (1) represents metamorphic zones for calcic rocks adopted by MIYASHIRO (1953a). Line (2) represents the MnO contents (% by weignt) of pyralspites in ordinary pelitic metamorphic rocks. A full line indicates that the mineral concerned is common and abundant, a broken line indicates that it is common but not abundant, and a dotted line indicates that it is rare.

The regional metamorphism in this district was clearly progressive in time. In the area transitional from zone A to B, blue-green hornblende usually occurs in a rim embracing a core of actinolite, and the plagioclase is strongly zoned with a rim much more calcic than the core. These indicate that actinolite and sodic plagioclase were produced at low temperatures and later with increasing temperature blue-green hornblende and more calcic plagioclase began to form, embracing the earlier-formed crystals. In the lower-grade part of zone C, some crystals of calciferous amphibole show zonal structure with a more greenish core and a brownish periphery. This structure also indicates a progressive change.

Probably, recrystallization and deformation took place generally simultaneously, but deformation outlasted recrystallization in the lower grades and recrystallization outlasted deformation in the higher grades. The grain sizes of metamorphic minerals depend largely on the intensity and time relation of recrystallization and deformation resulting in crushing.

Generally the grain sizes increase rather regularly with increasing grade of metamorphism. As regards basic rocks, the following shows the general ranges of size in mm.

Zones	A	B	C
Calciferous amphibole (length)	0.02–0.2	0.1–1	0.1–1
Plagioclase (diameter)	0–0.1	0–0.1	0.1–1

As regards pelitic and psammitic rocks, the following shows the general ranges of size in mm.

Zone	A	B	C
Biotite	0–0.2	0.1–1.5	0.1–2
Felspar	0–0.1	0–0.3	0.1–3

Thus, the grain size of colored minerals increases rapidly with passage from zone A to B, whereas that of colorless minerals increases rapidly with passage from zone B to C.

IV. PROGRESSIVE METAMORPHISM OF BASIC ROCKS

1. Original Rocks

Probably the basic metamorphic rocks were derived mostly from tuffs and other pyroclastics. At places basic rocks are finely interlayered with pelitic and psammitic materials, suggesting the original stratification. The boundary between basic and pelitic-psammitic rocks is usually parallel to the schistosity and compositional banding and probably represents the original bedding plane.

Relict minerals and textures are very rare. Usually all the minerals and textures of the original rocks were destroyed by the deformational movement and recrystallization during the metamorphism.

At several places basic sills and dykes were found to intrude the metamorphic rocks. Though they were transformed usually to have the same mineral composition as the basic rocks in the surroundings, the original textures are preserved commonly to some extent. For example, in a metamorphosed basic sill immediately west of the tunnel on the road between Saragai and Gosaisyo (zone B), Prof. Hisashi KUNO pointed out that the original chilled margins were transformed into a very fine-grained facies distinct from ordinary parts of the sill, though any relict mineral was not noticed. The distribution of the chilled margins within the sill indicates multiple intrusion of the magma.

The zoned plagioclases in ordinary basic metamorphic rocks have increasing An contents toward the margin. In some basic dykes, however, zoned plagioclases have decreasing An contents toward the margin. The more calcic core appears to represent a relict from the original igneous material. Thus, probably the original plagioclases tend to be better preserved in basics dykes than in basic rocks derived from pyroclastics.

Two exceptional rocks having relict minerals will be briefly described below: A rather massive rock (AM501018-2) from the river-bed of Samegawa about 500 m. southwest of Negisi (zone A) contains abundant relicts, up to 1.5 mm. in length, of porphyritic, light brownish-green hornblende in a fine-grained matrix now composed of albite, chlorite, actinolite, epidote and sphene. The hornblendes are commonly bent and show marginal alteration to actinolite. Some crystals of albite preserve the lath shape, up to 0.5 mm. in length, of the original plagioclases.

A biotite-amphibolite (AM 491104-11) from between Miyamae and Sakune (zone C) shows blastoporphyritic texture. The original phenocrysts, up to 2 mm. in size, are of augite and labradorite. The augite is now rimmed by brownish green common hornblende with the c axis in common. The labradorite is now rimmed by andesine. The original groundmass is now composed of small grains (0.05-0.3 mm. in size) of andesine, brownish green hornblende and biotite with a very small amount of quartz.

As discussed later, most of the metamorphosed basic rocks whose chemical composition may be regarded as having been nearly unchanged during metamorphism have normative olivine. The observed maximum content of normative olivine is about 17% by weight. SiO_2=45-48%, Na_2O=1.6-3.0%, K_2O=0.14-0.40%, and the ratio $Fe^{+2}/(Mg+Fe^{+2})$ ranges from 0.21 to 0.51. The poorness in K_2O is highly characteristic of these rocks. These compositions resemble those of olivine-basalts in the Hawaiian Islands. (The chemical variations during metamorphism will be treated later.)

2. Basic Rocks of Zone A

The basic metamorphic rocks of zone A are composed of actinolite, epidote, chlorite and sodic plagioclase (usually albite) with small amounts of apatite, sphene and opaque mineral. In some cases, small amounts of quartz, calcite and biotite were observed. By definition, actinolite is the only or main member of calciferous amphibole. The widespread occurrence of chlorite and the sodic composition of plagioclase also characterize this zone.

In most of the basic rocks, actinolite is more abundant than, or as abundant as chlorite. The basic rocks are generally very fine-grained. The actinolite is usually in fibrous crystals, less than 0.2 mm. in length and 0.01 mm. in diameter. The grains of epidote and albite are less than 0.1 mm. in diameter. The fineness in grain size is due to the crushing by the deformational movement during and after metamorphic recrystallization. Some crystals are bent.

The rocks show darker or lighter bluish green color. They have planar schistosity and mostly show more or less developed compositional banding (lamination) along the schistosity plane.

Nos. 1, 2, and 3 in Tables 2a and 2b give the compositions and norms of three examples in which actinolite is more abundant than chlorite. No. 4 of the same tables represents a rock in which actinolite is less abundant than chlorite. There is no systematic difference in CaO content between the two cases. In the rock of No. 4, the Ca is contained mostly in epidote and calcite. The Al/

$(Mg+Fe^{+2})$ ratio is mush higher in No. 4 than in Nos. 1, 2 and 3. Probably this is partly responsible for the difference in the proportion of actinolite to chlorite between the two cases.

Chlorite-rich schists similar to the rock of No. 4 were found to occur at

Table 2a. Basic metamorphic rocks of zone A, together with a more acidic one.

No.	1	2	3	4	5
SiO_2	45.97	46.39	47.79	48.89	66.82
Al_2O_3	14.21	13.06	12.43	14.81	11.43
TiO_2	1.12	1.35	0.58	1.15	0.69
Fe_2O_3	2.42	4.94	2.80	2.71	4.61
FeO	7.74	11.93	7.18	5.99	4.55
MnO	0.18	0.24	0.18	0.22	0.12
MgO	11.87	7.50	9.81	8.71	1.91
CaO	10.80	8.88	12.99	10.28	2.39
Na_2O	1.62	1.87	1.63	1.16	3.80
K_2O	0.14	0.16	0.19	0.67	1.49
H_2O+	3.92	3.90	1.81	5.42	2.28
H_2O-	0.39	0.23	0.74	0.21	0.29
P_2O_5	0.08	0.10	0.08	0.08	0.15
CO_2	n.d.	n.d.	1.85	n.d.	n.d.
	100.46	100.55	100.06	100.30	100.53

No. 1: Chlorite-epidote-actinolite-schist (AM 550909–14) from Saragai, Tono-mati. It is composed of actinolite (γ=1.648, $2V_X$=82°), epidote, chlorite (β=1.610, $\gamma-\alpha$=0.004, $2V_Z$=40°) and albite with very small amounts of opaque mineral, sphene(?) and calcite. Analyzed by H. HARAMURA.

No. 2: Chlorite-epidote-actinolite-schist (AM 550909–2) from Negisi, Tono-mati. It shows compositional banding. The mafic bands are composed of actinolite (γ=1.662, $2V_X$=72°), chlorite (β=1.635, $\gamma-\alpha$=0.001, opt. positive), epidote, albite and unidentified dust with very small amounts of biotite and opaque mineral. The felsic bands are composed of albite (β=about 1.538, $2V_Z$=about 74°), quartz and chlorite with a very small amount of biotite. Analyzed by H. HARAMURA.

No. 3: Chlorite-epidote-actinolite-schist (AM 550909–13) from Saragai, Tono-mati. It shows compositional banding. The mafic bands are composed of actinolite (γ=1.651), chlorite (β=1.624), epidote and albite with very small amounts of hornblende (γ=1.664, $2V_X$=75°) and biotite. Some felsic bands are composed of albite (β=about 1.538, $2V_Z$=82°) with small amounts of hornblende, actinolite, biotite, apatite and opaque mineral. Other felsic bands are composed of calcite, albite, and quartz with small amounts of actinolite, hornblende, sphene, chlorite and axinite(?). Analyzed by H. HARAMURA.

No. 4: Actinolite-epidote-chlorite-schist (AM 501018–15) from Taki, Tono-mati. It is composed of chlorite (β=1.617, $\gamma-\alpha$=0.004, $2V_Z$=40°) and epidote with smaller amounts of actinolite (γ=1.649), quartz, albite and calcite. Very small amounts of opaque mineral, biotite and unidentified dust are also present. Calcite and quartz tend to form light-colored bands. Analyzed by H. HARAMURA.

No. 5: Epidote-chlorite-albite-quartz-schist (AM 501018–4) from Taki, Tono-mati. In the chlorite, β=1.633, $\gamma-\alpha$=0.004 and $2V_X$=30°. It contains also small amounts of green tourmaline with brownish tinge, biotite and opaque mineral. Analyzed by H. HARAMURA.

Table 2b. C.I.P.W. norms of the rocks in Table 2a.

No.		1	2	3	4	5
Q		—	1.25	—	5.53	29.1
F	or	0.83	0.95	1.11	3.90	8.9
	ab	13.70	15.83	13.63	9.96	32.0
	an	31.09	26.76	26.15	33.10	9.7
di	en	6.42	3.61	10.24	5.12	0.2
	fs	2.24	3.17	4.35	1.45	0.4
	wo	9.38	6.94	15.68	7.20	0.6
hy	en	10.54	15.06	11.75	16.76	4.5
	fs	3.83	12.93	4.88	5.01	5.3
O	fo	8.85	—	1.69	—	—
	fa	3.53	—	0.82	—	—
mt		3.21	7.15	4.17	3.94	6.7
il		2.09	2.57	1.06	2.12	1.4
ap		0.19	0.23	0.34	0.34	0.3
Total		95.90	96.45	95.87	94.43	99.1
Total femic		50.28	51.66	54.98	41.94	19.4
an/(ab+an)		0.69	0.63	0.66	0.77	0.23
$Fe^{+2}/(Mg+Fe^{+2})$		0.21	0.40	0.29	0.28	0.57
$Fe^{+3}/(Fe^{+2}+Fe^{+3})$		0.22	0.27	0.26	0.29	0.48

separated places usually within the lower-grade part of zone A. They do not form a definite zone. It follows that chlorite-epidote-actinolite-schists with chlorite$>$ actinolite and with chlorite $<$actinolite were formed at similar temperatures and solid pressures. In some cases, however, locally higher H_2O and/or CO_2 pressures may have promoted to decompose actinolite into calcite and chlorite. Some amounts of SiO_2 and alkalies may have been introduced from outside together with H_2O and CO_2 during such processes. The rock of No. 4 has modal and normative quartz and a higher K_2O content than those of Nos. 1, 2 and 3.

The compositional banding was probably formed mainly by segregation of materials under the action of introduced hydrous solutions containing CO_2, SiO_2, alkalies, B, etc. Some bands are rich in albite and quartz, and some bands are rich in calcite together with albite and quartz. In basic schists, biotite is usually confined to the light-colored bands. In certain parts of the zone, numerous quartz veins, usually up to 50 cm. in width, run along the schistosity, and the smaller veins are indistinguishable from quartzose compositional bands of the schists.

The $Fe^{+2}/(Mg+Fe^{+2})$ ratios of basic metamorphic rocks of this zone range generally from 0.20 to 0.40. With the increase of this ratios, the rocks change from light bluish green to dark bluish green to the unaided eye, the actinolite in them becomes deeper in color under the microscope, and the refractive indices of the actinolite as well as of the associated chlorite become higher (Fig. 8).

The $Fe^{+3}/(Fe^{+2}+Fe^{+3})$ ratios of the analyzed rocks range from 0.22 to 0.29. These values are generally higher than the corresponding values in the higher-grade zones. The H_2O_+ contents of the rocks of this zone are generally higher than those of higher-grade zones.

Metamorphic rocks that appear to have been derived from more acidic igneous materials were found rarely. An example from Taki, Tono-mati, is shown in No. 5 of Tables 2a and 2b.

3. Transition from Zone A to B

Zone A, characterized by actinolite, and zone B, characterized by blue-green common hornblende, are gradational to each other. This means that both actinolite and blue-green hornblende occur in association in the transitional area, and does not mean that the actinolite changes continuously to blue-green hornblende with increasing grade. Probably there is a compositional gap between the two amphiboles under the physical conditions concerned.

It is in the higher-grade part of zone A that a small amount of blue-green hornblende begins to coexist with actinolite. With increasing grade, blue-green hornblende increases in amount. The blue-green hornblende occurs sometimes as a rim embracing an actinolite crystal, sometimes as patches within an actinolite crystal, and sometimes as independent crystals. In all the cases, the boundary between the two amphiboles is sharp. Even when the boundary looks to be somewhat gradational under the ordinary microscope, examination of thin sections tilted in appropriate angle on the universal stage revealed that the boundary is actually sharp. Thus, there is no gradational passage from actinolite to blue-green hornblende.

SHIDÔ (1958) shows that a blue-green hornblende from the lowest-grade part of zone B in the present district has about 11% Al_2O_3, similarly as ordinary hornblendes in the higher-grade part of the same zone. Then, the compositional variation from actinolite to blue-green hornblende is abrupt, and probably discontinuous.

The blue-green hornblende is higher in refractive indices, lower in birefringence and deeper in color than the associated actinolite. The former tends to form prismatic crystals, whereas the latter occurs in fibers and in bundles of fibers.

4. Basic Rocks of Zone B

In the lower-grade part of zone B, blue-green common hornblende is associated with a smaller quantity of actinolite, whereas in the higher-grade part the latter disappears and the former becomes deeper in color. Chlorite and epidote are confined to the lower-grade part. At the entrance to zone B, the plagioclase is usually oligoclase (about 20–30% An), and it becomes rapidly more calcic with increasing grade, up to labradorite composition within the lower-grade part of this zone. (The very remarkable reverse zoning of the plagioclase will be described and discussed later.) The plagioclase increases in amount with increasing grade.

Thus, the bulk of basic metamorphic rocks in the higher-grade part of zone B is represented by hornblende-plagioclase-schist or amphibolite, mainly composed of blue-green hornblende and plagioclase (andesine and labradorite) with small amounts of apatite, sphene and opaque mineral. Quartz, biotite, or clinopyroxene occurs in some cases.

The blue-green hornblende is highly aluminous (Al_2O_3=11.7–12.8%). The aluminous molecules of hornblende and the anorthite molecule of plagioclase would have been formed by the reaction of chlorite, epidote, actinolite and albite, as exemplified below:

$$\underset{\text{chlorite}}{3H_8Mg_5Al_2Si_3O_{18}}+\underset{\text{epidote}}{6HCa_2Al_3Si_3O_{13}}+7SiO_2 = \underset{\text{tschermakite mol.}}{5H_2Ca_2Mg_3Al_4Si_6O_{24}}+\underset{\text{anorthite mol.}}{2CaAl_2Si_2O_8}+10H_2O$$

$$\underset{\text{chlorite}}{14H_8Mg_5Al_2Si_3O_{18}}+\underset{\text{epidote}}{24HCa_2Al_3Si_3O_{13}}+\underset{\text{actinolite}}{H_2Ca_2Mg_5Si_8O_{24}}+28SiO_2 = \underset{\text{tschermakite mol.}}{25H_2Ca_2Mg_3Al_4Si_6O_{24}}+44H_2O$$

$$\underset{\text{albite}}{2NaAlSi_3O_8}+\underset{\text{actinolite}}{H_2Ca_2Mg_5Si_8O_{24}}=\underset{\text{sodatremolite mol.}}{H_2Na_2CaMg_5Si_8O_{24}}+\underset{\text{anorthite mol.}}{CaAl_2Si_2O_8}+4SiO_2$$

$$\underset{\text{albite}}{2NaAlSi_3O_8}+\underset{\text{actinolite}}{H_2Ca_2Mg_5Si_8O_{24}}=\underset{\text{Ha' molecule}}{H_2Na_2Ca_2Mg_5Al_2Si_6O_{24}}+8SiO_2$$

The coexistence of actinolite and blue-green hornblende ends in the middle of zone B by the disappearance of the former. This is perhaps due to the enlargement of the composition field of hornblende with increasing grade, resulting in vanishing of the miscibility gap between actinolite and hornblende.

In zone B, common hornblende is usually much larger (0.1–1 mm in length)

Table 3a. Basic metamorphic rocks of zone B.

No.	1	2	3
SiO_2	47.19	47.57	44.92
Al_2O_3	14.63	15.46	17.51
TiO_2	2.06	1.34	1.60
Fe_2O_3	1.92	1.47	2.82
FeO	11.11	8.87	8.72
MnO	0.39	0.29	0.16
MgO	7.38	9.77	7.23
CaO	10.42	10.39	13.62
Na_2O	2.95	2.49	1.49
K_2O	0.26	0.40	0.27
H_2O+	1.63	1.93	1.52
H_2O-	0.10	0.18	0.04
P_2O_5	0.13	0.12	0.18
	100.17	100.28	100.08

No. 1: Actinolite-hornblende-plagioclase-schist (AM 470620–9) from between Saragai and Gosaisyo, Tono-mati. It is a fine-grained rock composed of zoned amphibole, with an actinolite core (γ=1.665, $2V_X$=78°) and hornblende rim (γ=1.680, $2V_X$=70°), and zoned plagioclase (core An_{37}, rim An_{62}) with small amounts of epidote and opaque mineral. Analyzed by H. HARAMURA.

No. 2: Hornblende-plagioclase-schist (AM 470621–4) from between Gosaisyo and Saibati, Tabito-mura. It is composed of hornblende (γ=1.665, $2V_X$=85°) and zoned plagioclase (core An_{25-35}) with small amounts of opaque minerals (ilmenite and chalcopyrite ?), chlorite (β=1.608), epidote and sphene. Analyzed by H. HARAMURA.

No. 3: Epidote-hornblende-plagioclase-schist (AM 470621–16) from Kamiyama, Tabito-mura. It is composed of hornblende (γ=1.673, $2V_X$=82°) and zoned plagioclase (core An_{31}, rim An_{65}) with some amounts of epidote and opaque mineral. The distribution of epidote is very uneven, suggesting that it was introduced in a retrogressive stage. Analyzed by H. HARAMURA. The analysis of the hornblende is shown in Tables 6a and 6b, No. 1.

Table 3b. C.I.P.W. norms of the rocks in Table 3a.

No.		1	2	3
Q		—	—	—
F	or	1.67	2.23	1.60
	ab	25.17	20.97	12.58
	an	25.60	30.04	40.33
di	en	5.52	5.32	6.35
	fs	4.75	2.90	4.00
	wo	10.57	8.71	10.90
hy	en	0.80	4.02	3.21
	fs	0.66	2.11	2.00
O	fo	8.58	10.55	5.92
	fa	8.20	6.52	4.10
	mt	2.78	2.08	4.00
	il	3.95	2.58	3.04
	ap	0.34	0.34	0.40
Total		98.59	98.37	98.43
Total femic		46.15	45.13	43.92
an/(ab+an)		0.50	0.59	0.76
$Fe^{+2}/(Mg+Fe^{+2})$		0.46	0.34	0.40
$Fe^{+3}/(Fe^{+2}+Fe^{+3})$		0.14	0.13	0.23

than all the other minerals (usually less than 0.1 mm. in diameter). Elevated temperature of this zone appears to have promoted the formation of the large hornblendes. The much finer grain-size of plagioclase is probably due to crushing by deformational movement just as in zone A. In zone A, post-crystalline deformation of crystals is common, indicating that deformational movement outlasted recrystallization, whereas in zone B, deformed crystals are usually polygonized owing to recrystallization after the deformation. Perhaps, the duration of recrystallization was longer in this zone than in zone A.

The rocks are generally blue-greenish black. They are strongly schistose. In some cases, (100) of the hornblendes tends to become parallel to the schistosity plane, and in others the cleavage plane does so. The direction of the schistosity plane varies complicatedly owing to the frequent presence of minor folding. Probably the folds are mostly due to flexural movement. In some of such folds, (100) of the hornblends tends to become parallel to the axial plane. Lineation is strong not uncommonly and especially where minor folding is well-developed. The lineation is formed by the subparallel arrangement of hornblende prisms, and is parallel to the fold axis (usually about N 10° W, 30°N). Compositional banding is strong in some cases and not so in others. Banded schists are usually composed of hornblende-rich bands and plagioclase-rich ones, and the former are thicker and so more voluminous than the latter.

Tables 3a and 3b give the compositions and norms of three specimens. No. 1 in the tables represents the metamorposed chilled margin of the basic dyke, mentioned before, just to the west of the tunnel on the road between Saragai and Gosaisyo in the lower-grade part of zone B. No. 2 is also from the lower-

grade part of zone B, whereas No. 3 is from the higher-grade part. All these rocks have more than 10% normative olivine.

It was stated before that some basic rocks of zone A contain a very small amount of biotite. In basic rocks of zone B, biotite occurs not uncommonly and sometimes in a large amount. The most common biotite-bearing type is biotite-hornblende-plagioclase-schist with some apatite and opaque mineral. Some biotite-bearing basic schists contain quartz, which usually tend to form separate bands nearly free from all the other constituents. Quartz grains in some of such bands show very strong preferred orientation. Biotite also tends to segregate in some cases. We have at least three possibilities regarding the origin of the biotite-bearing basic rocks: (1) Isochemical metamorphism of some K-rich igneous materials; (2) Isochemical metamorphism of basic materials mixed with some sediments; (3) Metamorphism accompanied with material transfusion (especially of K and Si).

The third possibility will be commented below. Hydrous solutions containing CO_2 would dissolve Si and K possibly with Al during their passage through metasediments. In some cases, the solutions would react with basic schists with removal of Ca and deposition of quartz and biotite, resulting in biotite-bearing basic rocks. In other places, the solutions would settle the dissolved Ca as deposition of calcite, clinopyroxene and grandite together with quartz and microcline, resulting in calcic bands and lenses in basic rocks. Thus, the biotite-bearing basic rocks may be in a mutually complementary relation to calcic bands and lenses. (Calcic bands and lenses will be described later.)

Cummingtonite is very rare in this zone.

Clinopyroxenes of the diopside-hedenbergite series begin to occur as a constituent of thin calcic bands and lenses in basic metamorphic rocks from the lower-grade part of zone B. These bands and lenses, though very thin, will be treated as an independent rock unit intercalated between basic rocks—under the grouping of calcic rocks—, because they are not always in stable equilibrium with the surrounding basic rocks.

5. Basic Rocks of Zone C

Basic metamorphic rocks of zone C are composed of common hornblende and plagioclase, frequently associated with biotite, cummingtonite, and/or quartz. Usually small amounts of apatite and opaque mineral also occur. Sphene is scarce.

By definition, the common hornblende has green, yellow-brownish green or brownish yellow axial color without bluish tinge for Z. The common occurrence of cummingtonite and biotite also is characteristic of this zone. Then, the common types of basic rocks are amphibolite, cummingtonite-amphibolite (plagioclase + hornblende + cummingtonite), biotite-amphibolite (plagioclase + hornblende + biotite) and cummingtonite-biotite-amphibolite. Clinopyroxene-bearing amphibolite is not rare. The Ti of sphene of zone B was mostly probably absorbed by amphiboles and biotite in this zone.

The grains of plagioclase become rapidly coarser at the entrance to this zone. Then, usually they are as coarse as hornblendes (0.1–1 mm in size).

The rocks are black or greenish black to the unaided eye, having moderate planar schistosity and lineation. Compositional banding is conspicuous in some cases and inconspicuous in others.

The common occurrence of cummingtonite would be a result of the compositional variation in hornblende such as the decomposition of the tschermakite

molecule in passage from zone B to C. At the elevated temperatures of zone C, diffusion of K-bearing material into basic rocks was probably increased, and the K was probably readily fixed by the transformation of the cummingtonite into biotite, resulting in the characteristically widespread occurrence of biotite-bearing rocks. Most of the biotite-bearing basic rocks are devoid of quartz, and then could not have been produced from basic materials mixed with pelitic or psammitic sediments which are usually rich in quartz.

Tables 4a and 4b give the compositions and norms of three basic rocks. Nos. 1 and 2 of the table are characterized by high contents of K as well as of Na. It is noteworthy that No. 1 has normative nepheline.

Table 4a. Basic metamorphic rocks of zone C.

No.	1	2	3
SiO_2	44.21	50.86	45.39
Al_2O_3	15.52	19.67	14.89
TiO_2	0.06	1.69	2.32
Fe_2O_3	3.12	1.93	0.34
FeO	9.47	8.86	13.40
MnO	0.20	0.22	0.34
MgO	11.82	3.85	7.17
CaO	9.56	7.95	11.36
Na_2O	3.31	3.30	1.85
K_2O	0.74	1.20	0.27
H_2O_+	1.65	0.44	2.86
H_2O_-	0.19	0.10	0.15
P_2O_5	0.24	0.26	0.23
	100.09	100.33	100.57

No. 1: Biotite-amphibolite (AM 470808–3) from Kamata, Hurudono-mura. It is composed of hornblende ($\gamma=1.680$, $2V_X=83°$) and plagioclase (An_{20-25}) with a smaller amount of biotite ($\gamma=1.624$). Very small amounts of opaque mineral, apatite and sphene are also present. This rock has a nepheline-basanitic composition. Analyzed by H. HARAMURA. The analysis of the hornblende is shown in Tables 6a and 6b, No. 4.

No. 2: Cummingtonite-biotite-amphibolite (AM 470802–1) from west of Daibara, Hurudono-mura. It is composed of plagioclase (dirty core An_{47}, clear rim An_{28}), hornblende ($\gamma=1.678$) and biotite ($\gamma=1.659$) with small amounts of cummingtonite ($\gamma=1.678$, $2V_Z=84°$), quartz, opaque mineral and apatite. Neither olivine nor quartz is present in the norm (Table 4b). Analyzed by H. HARAMURA.

No. 3: Clinopyroxene-amphibolite (AM 470803–11) from between Otake and Tinoknbo (Sinokubo), Hurudono-mura. It is a schistose rock mainly composed of hornblende ($\gamma=1.679$, $2V_X=79°$) and plagioclase (core An_{55}, rim An_{75}) with small amounts of opaque mineral, sphene and apatite. Clinopyroxene-bearing bands, up to 0.5 mm thick, are intercalated in the rock at intervals of several mm. The bands are composed of hornblende, clinopyroxene and plagioclase with small amounts of opaque mineral, sphene and apatite. The hornblende of the rock in general has the same optical properties as that of the bands. Analyzed by H. HARAMURA. The analysis of the hornblende is shown in Tables 6a and 6b, No. 3.

Table 4b. C.I.P.W. norms of the rocks in Table 4a.

No.		1	2	3
	ne	8.81	—	—
F	or	4.45	7.24	1.60
	ab	11.53	27.80	15.73
	an	25.31	35.30	31.50
di	en	5.32	0.40	4.50
	fs	2.64	0.53	5.30
	wo	8.48	0.93	9.80
hy	en	—	9.04	3.81
	fs	—	11.88	4.55
O	fo	16.88	—	6.70
	fa	9.58	—	8.80
	mt	4.63	2.78	0.46
	il	0.15	3.20	4.40
	ap	0.67	0.67	0.50
Total		98.45	99.77	97.65
Total femic		48.35	29.43	48.82
an/(ab+an)		0.69	0.56	0.67
$Fe^{+2}/(Mg+Fe^{+2})$		0.31	0.56	0.51
$Fe^{+3}/(Fe^{+2}+Fe^{+3})$		0.23	0.16	0.02

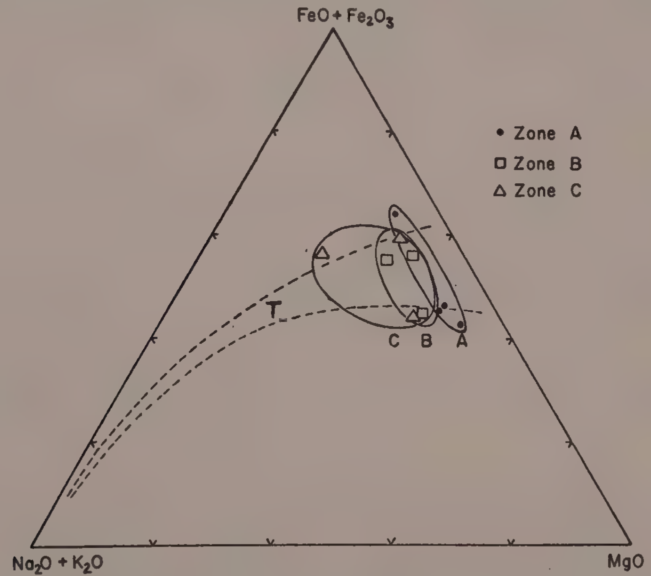

Fig. 5. Compositions of basic metamorphic rocks of the Gosaisyo-Takanuki district. The symbols (dots, squares and triangles) represent the metamorphic zones to which they belong. The composition fields for zones A, B and C are shown by full lines. The elongated field, *T*, shown by broken lines, represents the composition field of plutonic rocks in the Tabito composite mass of the older group after F. SHIDÔ (1958).

6. Chemical Changes with Advancing Metamorphism

With increasing grade of metamorphism, the H_2O_+ content and the $Fe^{+3}/(Fe^{+2}+Fe^{+3})$ ratio of basic rocks become generally lower.

The available analyses are plotted in Fig. 5. Nos. 1, 2 and 3 of Table 2 are probably near the compositions of the original basic rocks before metamorphism. It is clear that the contents of Na and K tend to increase with advancing metamorphism. This variation, although noticed slightly in passing from zone A to B, is very conspicuous in the formation of biotite-bearing basic rocks in zone C. Probably this variation is not due to variable amounts of admixed pelitic and psammitic sediments, but is due to the introduction of K from outside. Most of the biotite-bearing basic rocks are devoid of quartz which are usually abundant in sediments, as stated before. Moreover, the original rocks of zones A and B were deposited probably under similar conditions, and hence it is improbable that there was any systematic difference in the amount of admixed sediments between zones A and B. A similar progressive increase in K content of pelitic and psammitic rocks will be described in the next section.

V. PROGRESSIVE METAMORPHISM OF PELITIC AND PSAMMITIC ROCKS

1. Original Rocks and Chemical Changes

The available chemical analyses of pelitic and psammitic metamorphic rocks in this district are shown in Table 5. They have generally high SiO_2 and low Al_2O_3 contents in comparison with ordinary pelitic rocks of other districts.

The pelitic and psammitic rocks of zones A and B usually occur as beds intercalated between usually much thicker beds of basic rocks, whereas those of

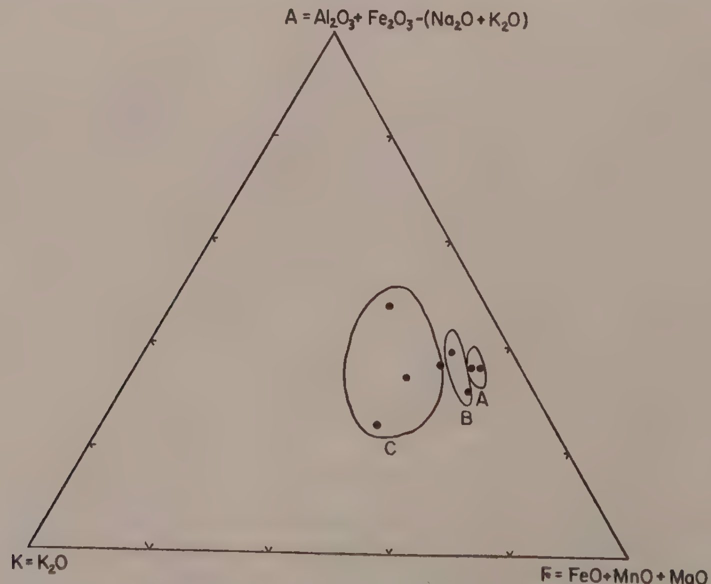

Fig. 6. AKF diagram for pelitic and psammitic metamorphic rocks of the Gosaisyo-Takanuki district. The composition fields for zones A, B and C are denoted by A, B and C respectively.

Table 5. Pelitic and psammitic metamorphic rocks of the Gosaisyo-Takanuki district.

Zone	A		B		C			
No.	1	2	3	4	5	6	7	8
SiO_2	69.91	62.18	64.22	68.23	77.37	63.28	63.75	89.93
Al_2O_3	12.73	14.81	12.64	10.84	12.38	17.98	17.10	4.38
TiO_2	0.80	1.09	0.64	0.46	0.27	0.77	0.67	0.12
Fe_2O_3	1.54	0.78	4.56	6.21	0.40	0.96	1.12	0.32
FeO	3.55	5.58	5.01	3.30	2.35	5.68	3.84	1.34
MnO	0.24	0.41	0.14	0.12	0.11	0.22	0.03	0.04
MgO	2.71	3.42	3.21	1.92	0.88	2.56	1.93	0.52
CaO	2.34	3.61	3.09	2.66	1.18	1.07	1.81	0.41
Na_2O	2.27	1.41	2.49	3.25	1.52	2.34	3.37	0.39
K_2O	1.85	2.02	2.75	1.88	2.46	3.71	4.29	2.01
H_2O_+	1.44	2.84	1.13	0.76	0.87	1.71	1.25	0.45
H_2O_-	0.27	0.13	0.21	0.22	0.09	0.09	0.22	0.10
P_2O_5	0.15	0.56	0.19	0.18	0.30	0.04	0.15	0.10
	99.80	98.84	100.28	100.03	100.18	100.41	99.53	100.11

No. 1: Pelitic and psammitic schists from zone A (a composite sample of 8 rocks). Analyzed by H. HARAMURA.

No. 2: Pyralspite-biotite-chlorite-quartz-schist (AM 501028–4a) from Negisi, Tonomati (zone A). Analyzed by T. MIYASHIRO (MIYASHIRO, 1953b). The analysis of the pyralspite is shown in Table 7, No. 1.

No. 3: Biotite-plagioclase-quartz-schists with and without muscovite from zone B (a composite sample of 3 rocks). Analyzed by H. HARAMURA.

No. 4: Pyralspite-biotite-plagioclase-quartz-schists with and without muscovite from zone B (a composite sample of 3 rocks). Analyzed by H. HARAMURA.

No. 5: Pelitic and psammitic genisses from zone C (a composite sample of 5 rocks). Analyzed by H. HARAMURA.

No. 6: Andalusite-sillimanite-garnet-cordierite-biotite-muscovite-microcline-quartz-gneiss (AM 470805–5) from between Huruuti and Onasawa, Hurudono-mura (zone C). Analyzed by H. HARAMURA.

No. 7: Muscovite-biotite-microcline-oligoclase-quartz-gneiss with very small amounts of sillimanite and pyralspite (AM 470802–16) from Yokogawa, Hurudono-mura (zone C). Analyzed by T. MIYASHIRO (MIYASHIRO, 1953 b). The analysis of the pyralspite is shown in Table 7, No. 5.

No. 8: Muscovite-biotite-plagioclase-quartz-gneiss with a very high content of quartz (AM 470802–11) from Yokogawa, Hurudono-muaa (Zone C). Analyzed by H. HARAMURA.

zone C usually occur in wide areas not associated with basic rocks. This difference in the conditions of deposition is probably responsible for the fact that pelitic and psammitic rocks of zones A and B are generally poorer in Al and richer in Ca than those of zone C.

With increasing grade of metamorphism, the H_2O_+ and Fe_2O_3 contents tend to decrease similarly as in the case of basic metamorphic rocks.

The analyses of Table 5 are plotted in the AKF diagram (Fig. 6). It is interesting that the points representing the compositions move generally toward the K corner with advancing metamorphism. This compositional change can be

hardly ascribed to a systematic difference in composition of the original sediments, because the rocks of zones A and B appear to have deposited under similar conditions to each other. Probably some amount of K was gradually introduced from outside with advancing metamorphism.

The progressive increase in K content is clearly revealed in the mineral compositions. Biotite is abundant in pelitic and psammitic rocks of all the zones. In zone A, biotite is almost the only K-rich mineral; muscovite is very rare. In zone B, muscovite is more common and microcline occurs rarely. In zone C, muscovite and K-felspar are common, and K-felspar is very abundant in some cases.

Some pelitic and psammitic rocks show fairly high Mn contents. It must have promoted the formation of pyralspite garnet.

2. Pelitic and Psammitic Rocks of Zone A

The most common type of pelitic and psammitic rocks in zone A is graphite-chlorite-biotite-quartz-schist. Quartz is the most abundant constituent. Generally biotite is much more abundant than chlorite. In addition, some rocks contain sodic plagioclase, some rocks contain muscovite (sericite), and some rocks contain pyralspite garnet, all in relatively small amounts. Calcite, tourmaline and opaque mineral also occur in minute quantities. In many thin sections, extremely fine grains of an unidentified mineral were observed to spread like dust. The mineral may be sphene or epidote.

The grains of quartz and felspar are usually smaller than 0.1 mm. in size, and those of biotite are smaller than 0.2 mm. Probably, crushing due to deformational movement have reduced the grain size. Some porphyroblasts of pyralspite have trails of minute inclusions indicating para-crystalline rotation. In lenses and bands almost exclusively composed of quartz, the quartz grains sometimes reach 0.2 mm in diameter. Probably, the lenses and bands were formed by metamorphic differentiation, and there recrystallization outlasted the deformational movement.

Recrystallization is complete and the texture of the original rocks has been destroyed by deformational movement and recrystallization. Schistosity and compositional banding are conspicuous. Usually the schistosity is parallel to the bedding and banding. However, where small shear folds are well-developed, a new schistosity parallel to the axial plane of the folds tends to be produced. This schistosity is oblique or normal to the bedding and banding. Examination under the microscope has revealed that biotite flakes were initially parallel to the bedding, and were later rotated to become parallel to the axial plane of the folds by the shear movements which took place on the closely spaced shear planes parallel to the axial plane. Various transitional states were observed.

3. Pelitic and Psammitic Rocks of Zone B

The pelitic and psammitic rocks in the lower-grade part of zone B are very similar to those in zone A, except that the plagioclase is usually more calcic (oligoclase and andesine) and dust of the unidentified fine-grained mineral disappears. (This suggests that the unidentified mineral is calciferous.)

In the higher-grade part of zone B, chlorite disappears and graphite decreases or disappears. Then, the most common type is biotite-plagioclase-quartz-schist. Some rocks contain muscovite, some rocks contain pyralspite and some rocks contain microcline. Tourmaline, apatite, and opaque mineral occur widely in minute

amounts. Rarely andalusite or blue-green hornblende was found.

The grain sizes of the constituent minerals are generally larger in this zone than in zone A. The grains of quartz and felspar are usually smaller than 0.3 mm, and those of biotite are smaller than 1.5 mm. In lenses and bands almost exclusively composed of quartz, however, the quartz grains sometimes reach 2 mm. in size. Pyralspite usually shows porphyroblastic development.

Schistosity and compositional banding are conspicuous in most cases. Usually the schistosity is parallel to the bedding and banding. Where minor folding is well-developed, biotite flakes tend to arrange parallel to the axial plane. Such folding appears to be sometimes due to shear and sometimes due to flexure. Petrofabric analysis on two rocks with microfolding showed that the c axes of the quartz grains make a girdle around the fold axis, maxima roughly normal and parallel to the limbs being noticed within the girdle.

4. Pelitic and Psammitic Rocks of Zone C

The most conspicuous feature of pelitic and psammitic rocks in this zone is the widespread occurrence of K-felspar (microcline and orthoclase) and sillimanite. The K-felspar may be in a fairly large amount. Then, the most common type is biotite-K-felspar-plagioclase-quartz-gneiss, usually with small amounts of muscovite, pyralspite and/or sillimanite. Some rocks contain andalusite and/or cordierite. Apatite, sphene, zircon and opaque mineral occur in very small amounts. Hornblende or cummingtonite occurs rarely.

The abundance of K-felspar in this zone is partly due to the higher K contents of the host-rocks as mentioned before, but is partly due to the decreasing stability of muscovite and biotite with rising temperature. Probably, muscovite begins to react with biotite having low Fe^{+2}/Mg ratios to form cordierite and K-felspar within the lower-grade part of zone C, as is shown by the following equation:

$$\overset{\text{muscovite}}{6H_2KAl_3Si_3O_{12}}+\overset{\text{biotite}}{2H_2KMg_3AlSi_3O_{12}}+\overset{\text{quartz}}{15SiO_2}=\overset{\text{cordierite}}{3Mg_2Al_4Si_5O_{18}}+\overset{\text{K-felspar}}{8KAlSi_3O_8}+8H_2O$$

In zone B, probably cordierite cannot coexist with K-felspar and, if so, it is to occur only in rocks without K-felspar whereas in zone C, cordierite can coexist with K-felspar and hence the occurrence of cordierite becomes probably much more frequent.

In the lower-grade part of zone C, both andalusite and sillimanite occur, whereas in the higher-grade part andalusite disappears. Hence the transition point from andalusite to sillimanite lies within the lower-grade part of zone C.

Probably in the higher-grade part of zone C, muscovite decomposes into sillimanite and K-felspar*, as follows:

$$\overset{\text{muscovite}}{H_2KAl_3Si_3O_{12}}+\overset{\text{quartz}}{SiO_2}=\overset{\text{sillimanite}}{Al_2SiO_5}+\overset{\text{K-felspar}}{KAlSi_3O_8}+H_2O$$

Then, sillimanite can coexist with K-felspar and hence its occurrence is very common though in a small amount. Some of such rocks, however, suffered slight retrogressive change to reproduce muscovite.

The grains of quartz and felspar are usually 0.2–3.0 mm. in size, and those of biotite are smaller than 2 mm. Bedding schistosity and gneissic banding are

* Muscovite shows small extents of substitutions Al–Fe^{+3} and K–Na. Then, the decomposition should take place in a temperature range and not in a definite temperature. The dwindling of the composition range of muscovite in the lower-grade part of zone C (to be described later) may be regarded as the begining of the decomposition.

well developed. Cursory petrofabric analysis was attempted for the c axes of quartz grains on four specimens of the gneisses. One specimen showed the maximum I of Sander (i.e. γ-rule), another showed the maximum IV, and the rest showed more complicated preferred orientation.

There are numerous pegmatitic veins and pockets characteristically in zone C. The high temperature that prevailed there probably promoted their formation. Some of the pelitic and psammitic rocks are very rich in K-felspar which may be in large grains. The K-felspar may have been introduced into the metamorphic rocks from nearby pegmatitic masses.

VI. PROGRESSIVE METAMORPHISM OF CALCIC ROCKS*

1. Calcic Bands and Lenses in Basic Metamorphic Rocks

Bands and lenses, usually up to a few cm. thick, of calcic compositions are widespread in basic rocks of this district. They are generally concordant to the schistosity of the surrounding basic metamorphic rocks.

In zone A, they are represented by bands and lenses composed of quartz, sodic plagioclase (usually albite) and calcite, sometimes with small amounts of epidote and actinolite. These rocks are mineralogically similar to calcite-bearing bands of ordinary banded schists. Then, we need not treat them as independent rocks.

In the lower-grade part of *zone B*, clinopyroxenes of the diopside-hedenbergite series begin to occur in calcic bands and lenses, and in the middle of the zone grandite garnet also begins to occur. Then, calcic bands and lenses in the higher-grade part of zone B are usually composed of quartz, plagioclase (albite to labradorite), epidote, grandite, clinopyroxene, microcline and calcite with small amounts of apatite and sphene though some bands and lenses are free from grandite and calcite. Hornblende may occur where grandite and calcite are absent. The hornblende shows the same color as that of the surrounding basic rocks.

The grandite-quartz and calcite-quartz assemblages in the bands and lenses are not compatible with common hornblende in the surrounding basic metamorphic rocks, as is suggested by the following equations:

$$\underset{\text{grossularite}}{3Ca_3Al_2Si_3O_{12}}+\underset{\text{tschermakite mol.}}{2H_2Ca_2Mg_3Al_4Si_6O_{24}}+\underset{\text{quartz}}{5SiO_2}=\underset{\text{anorthite}}{7CaAl_2Si_2O_8}+\underset{\text{diopside}}{6CaMgSi_2O_6}+2H_2O$$

$$\underset{\text{calcite}}{3CaCO_3}+\underset{\text{tschermakite mol.}}{H_2Ca_2Mg_3Al_4Si_6O_{24}}+\underset{\text{quartz}}{4SiO_2}=\underset{\text{anorthite}}{2CaAl_2Si_2O_8}+\underset{\text{diopside}}{3CaMgSi_2O_6}+3CO_2+H_2O$$

For this reason, bands and lenses having grandite and/or calcite are usually separated from the surrounding basic metamorphic rocks on both sides by films that do not contain grandite nor calcite. The films are usually 1–2 mm thick, and are composed of abundant clinopyroxene and relatively calcic plagioclase with small amounts of quartz and sphene.

Epidote persists to the higher-grade part of zone B in calcic rocks. The plagioclases are usually more sodic than those of surrounding rocks.

The analysis of a calcic lens (AM 550910–4) from Isizumi, Tabito-mura, in the higher-grade part of zone B is given below: SiO_2 52.43, Al_2O_3 15.44, TiO_2 0.97, Fe_2O_3 7.66, FeO 4.54, MnO 0.20, MgO 3.89, CaO 10.31, Na_2O 2.66, K_2O 1.06,

* The term *calcic rocks* means the rocks in which Ca is very abundant in comparison with Al and with $Mg+Fe^{+2}$. For detailed descriptions of representative specimens, see MIYASHIRO (1953a).

H_2O_+ 0.69, H_2O_- 0.34, P_2O_5 0.23, Total=100.42 (analysed by H. HARAMURA). This lens, 2 cm. thick, is composed of quartz, clinopyroxene ($Di_{65}Hd_{35}$), microcline, blue-green hornblende (γ=1.677, $2V_x$=67°, $c \wedge Z$=19°), andesine, opaque mineral, epidote and apatite in decreasing order. The high contents of Fe_2O_3 and K_2O and low content of MgO in comparison with the surrounding basic metamorphic rocks are characteristic. The absolute amount of CaO is not so large.

Calcic bands and lenses in basic rocks of *zone C* differ from those of the higher-grade part of zone B in the following points: (1) In zone C, epidote disappears; (2) grandite becomes very rare, probably owing to increased diffusion of Mg, Fe, etc. from the surrounding basic rocks at elevated temperatures; (3) Hornblende loses bluish tinge, usually becoming yellowish or brownish just as that of the surrounding rocks. Usually, the plagioclases of such bands and lenses are different in composition from those of the surrounding basic rocks.

In some parts of zone C, wollastonite occurs in calcic rocks.

The origin of calcic bands and lenses is a difficult problem. They are genetically related to the basic metamorphic rocks, because they occur only in basic rocks and because the grade of their metamorphism increases generally with that of the surrounding basic rocks. They were not always in equilibrium, however, with the surrounding basic rocks. For example, calcic bands and lenses are usually rich in quartz and sometimes also rich in microcline, whereas most of the surrounding basic metamorphic rocks are devoid of quartz and have much normative olivine, and are very poor in K. The presence of grandite-quartz assemblage in calcic rocks also indicates lack of equilibrium. The plagioclase of these rocks differs in composition from that of the surrounding basic rocks.

These calcic rocks cannot have been formed by simple diffusion of calcic materials from the surrounding basic rocks, because this process is a change from a stable to an unstable state.

Probably these calcic rocks were not derived from impure calcareous sediments, because they differ from such sediments in chemical composition, especially in $(Fe^{+2}+Fe^{+3})/Mg$ ratio.

The following two explanations are possible. First, they may represent metamorphosed calcic masses that were originally formed by some hydrothermal or deuteric action on the associated basic rocks before the regional metamorphism.

Secondly, they may have been formed through some complicated processes of material migration involving bodily flow of solution in the metamorphic terrain, as was already discussed, for example, in connection with the possible complementary relation of biotite-bearing basic rocks with calcic ones (p. 237).

In the higher-grade part of zone B, the surrounding basic rocks do not contain epidote, whereas calcic bands and lenses in them contain epidote together with plagioclase usually more sodic than that of the surrounding basic rocks. Relatively high Fe^{+3}/Al ratios of these calcic rocks in comparison with those of the surrounding basic rocks may be responsible for the formation of epidote in this high grade. Otherwise, the calcic rocks may have suffered retrogressive readjustment in declining stages of metamorphism.

2. Limestones

Limestones are very rare in zones A and B. At Ôdaira in the highest-grade part of zone A, a small limestone bed, less than 10 cm. thick, was found to be intercalated conformably between biotite schist. It is the only limestone I found in zone A, and is composed of calcite with very small amounts of quartz and

epidote. At a locality between Gosaisyo and Saibati in the lower-grade part of zone B, several thin layers of limestone, each 20–30 cm. thick, were found to be intercalated conformably between amphibolite. They are mainly composed of calcite with very small amounts of quartz, epidote, actinolite. chlorite, sodic plagioclase and microcline. In these cases, grains of calcite are generally less than 1 mm. in diameter (frequently 0.05–0.1 mm.).

There are a few tens of limestone beds in zone C. Usually they are from 1 to several meters thick, and are intercalated between pelitic and psammitic gneisses. The limestones are composed of calcite with very small amounts of quartz, clinopyroxene, grandite, wollastonite, plagioclase, K-felspar, scapolite, sphene, apatite, and graphite. Hornblende may occur where quartz is not present. Only in two limestones, some amounts of dolomite were found. These limestones contain forsterite, tremolite, clinopyroxene, phlogopite, and graphite. Grains of calcite in limestones of zone C are usually 1 to 10 mm. in diameter and sometimes show strong deformation and preferred orientation.

VII. MINERALOGY

1. Plagioclases*

(a) Plagioclases in Basic Metamorphic Rocks

In basic metamorphic rocks of zone A, the plagioclase is clear and homogeneous, having the composition of about 7–15% An. Most of the Na present in the rocks is contained in plagioclase, and hence the amount of plagioclase may be estimated at 10–15% from the Na content of the rocks. Near the boundary to zone B, the plagioclase becomes to have compositions of about 20–30% An.

At the lowest-grade part of zone B, the plagioclase has the composition of about 30% An. With increasing grade it becomes rapidly more calcic up to 50–65% An within the lower-grade part of zone B. The plagioclase there amounts to about 40–50% in ordinary basic rocks. The grains of plagioclase in zone B are usually strongly zoned with a rim more calcic than the core, representing progressive compositional variation with advancing metamorphism.

In the higher-grade part of the lower half of zone B, plagioclase grains of basic metamorphic rocks usually show strong zonal structure having an andesine core (30–40% An) and a labradorite rim (50–65% An). The boundary is sharp, showing a Becke line. In some grains, the more sodic core contains minute blebs or strings of more calcic plagioclase having the same composition as the rim. The lack of the compositions between 40 and 50% An is very remarkable. Perhaps it is due to the existence of a *miscibility gap* in this composition range in such low temperatures. Two plagioclases on both sides of the gap seem to occur in stable equilibrium with each other. In the higher-grade half of zone B, the boundary between the andesine core and labradorite rim becomes gradually less sharp, and some rocks contain plagioclases with 40–50% An. Then, the miscibility gap perhaps vanishes in the middle of zone B.

In zone C, the plagioclases in basic rocks are usually in the composition range of 50–85% An. Rather rarely more sodic plagioclases, down to 20% An, were found. It is noteworthy that the An contents of plagioclase in basic rocks of zone C tend to be higher than those in basic rocks of zone B. This may be

* The compositions of plagioclases were determined from the indices α and γ measured by the immersion method on the basis of Chayes' (1952) curve.

partly due to the complete conversion of epidote to An molecule, but is probably mainly due to the compositional variation of the associated hornblende with increasing metamorphism. (The destruction of some of tschermakite molecule should produce An molecule together with cummingtonite, whereas the increase in Na-bearing molecules should result in a decrease of Ab molecule.) Plagioclases in basic rocks of zone C are sometimes homogeneous and sometimes weakly zoned with gradually increasing An content toward the margin.

(b) Plagioclases in Pelitic and Psammitic Metamorphic Rocks

The plagioclases in pelitic and psammitic metamorphic rocks are usually albite in zone A, and oligoclase and andesine in zones B and C. These rocks are not so rich in Ca as to produce more calcic plagioclases.

2. Calciferous Amphiboles

Calciferous amphiboles have been used as the index minerals for zonal mapping. Zone A is characterized by actinolite, zone B is characterized by common hornblende with blue-green axial color for *Z*, and zone C is characterized by common hornblende without bluish tinge (i.e. hornblende with green, yellow-brownish green or brownish yellow axial color for *Z*).

The optic angle and index γ of the calciferous amphiboles are plotted on a rectangular diagram (Fig. 7). Actinolites of zone A fall in a field quite different from those of common hornblendes of zones B and C. The field of hornblendes of zone C is smaller than that of zone B.

In *zone A*, actinolite occurs as fibers, usually making bundles. In ordinary thin sections, $X=Y=Z=$nearly colorless for actinolites with $\gamma=$about 1.65, and $X=$very pale yellow, $Y=$pale green with brownish tinge, and $Z=$pale bluish green for actinolites with $\gamma=$about 1.66. The observed index γ ranges from 1.648 to

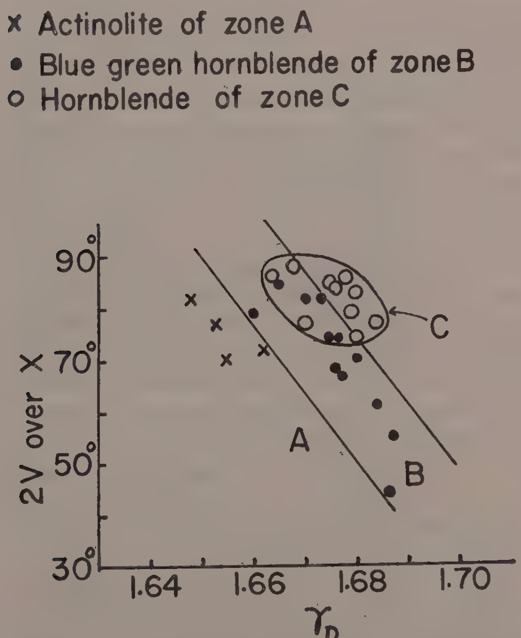

Fig. 7. Optic angle and index γ of calciferous amphiboles of the Gosaisyo-Takanuki district.

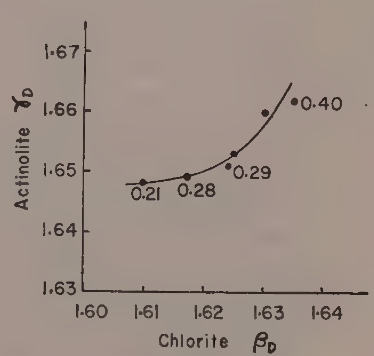

Fig. 8. Relation between index β of chlorite and index γ of the associated actinolite in actinolite-chlorite-schists of zone A. The numbers attached to four points represent the $Fe^{+2}/(Mg+Fe^{+2})$ ratios of the host-rocks. (For the data underlying this figure, see Tables 2a and 2b.)

1.662. The refractive indices of actinolite and associated chlorite increase with the Fe^{+2}/Mg ratio of the host-rock (Fig. 8). Then, we may consider that the variation in refractive indices of actinolites is mainly governed by the Fe^{+2}/Mg

Table 6a. Hornblendes from basic metamorphic rocks of the Gosaisyo-Takanuki district.

Zone	B		C		
No.	1	2	3	4	5
SiO_2	44.07	40.96	44.36	43.20	42.44
Al_2O_3	12.37	11.70	11.69	12.44	12.50
TiO_2	1.70	0.99	1.26	1.65	3.09
Fe_2O_3	0.18	5.32	1.29	3.21	2.07
FeO	10.23	13.30	16.63	10.10	12.38
MnO	0.18	0.69	0.43	0.21	0.30
MgO	14.20	11.06	9.71	13.27	11.43
CaO	12.42	12.72	11.82	11.36	10.90
Na_2O	1.00	1.06	0.79	2.72	2.21
K_2O	0.30	1.27	0.50	0.40	0.14
H_2O_+	2.85	1.50	1.67	1.38	1.94
H_2O_-	0.03	0.06	0.12	0.07	0.15
F	n.d.	0.13	n.d.	n.d.	n.d.
P_2O_5	n.d.	n.d.	0.12	0.07	0.23
	99.53	100.76	100.39	100.08	99.78
α_D	1.656	1.663	1.650	1.654	1.653
γ_D	1.673	1.686	1.679	1.680	1.676
$2V_X$	82°	44°	79°	83°	84°
$c \wedge Z$	19°	25°	15°	19°	15°

No. 1: Bluish green hornblende from epidote-hornblende-plagioclase-schist (AM 470621–16) from Kamiyama, Tabito-mura (middle-grade part of zone B). X=very pale yellow, Y=pale yellowish-brownish green, and Z=bluish green with $Z=Y>X$. Analyzed by T. MIYASHIRO (MIYASHIRO, 1953a). For the host rock, see Tables 3a and 3b, No. 3.

No. 2: Bluish green hornblende from a clinopyroxene-rich lens in amphibolite (AM 470803–12) from Domeki, Hurudono-mura (higher-grade part of zone B). X=yellow, Y=dark yellowish green, and Z=bluish green with $Y>Z>X$. Analyzed by T. MIYASHIRO. For the host-rock, see MIYASHIRO (1953a, p. 90). The associated clinopyroxene was also analyzed (Table 9).

No. 3: Yellowish-brownish green hornblende from clinopyroxene-amphibolite (AM 470803–11) from between Otake and Tinokubo, Hurudono-mura (zone C). X=very pale yellow, Y=yellowish-greenish brown, and Z=yellowish brownish green with $Z=Y>X$. Analyzed by H. HARAMURA. For the host-rock, see Tables 4a and 4b, No. 3.

No. 4: Greenish brown hornblende from biotite-amphibolite (AM 470808–3) from Kamata, Hurudono-mura (zone C). X=very pale yellow, Y=greenish-yellowish brown, and Z=greenish brown with $Z=Y>X$. Analyzed by H. HARAMURA. For the host-rock, see Tables 4a and 4b, No. 1.

No. 5: Brown hornblende from amphibolite at Yokogawa, Hurudono-mura (zone C). X=pale yellow, Y=sepia brown, and Z=sepia brown with $Z>Y>X$. Analyzed by S. TANAKA (TSUBOI, 1935).

Table 6b. Atomic ratios of hornblendes of Table 6a calculated on the anhydrous basis of O=23.

Zone	B		C		
No.	1	2	3	4	5
Si	6.453	6.128	6.573	6.291	6.277
Al^{IV}	1.547	1.872	1.427	1.709	1.723
Al^{VI}	0.588	0.191	0.615	0.425	0.455
Ti	0.187	0.111	0.141	0.181	0.344
Fe^{+3}	0.019	0.598	0.144	0.352	0.231
Fe^{+2}	1.252	1.663	2.060	1.230	1.531
Mn	0.022	0.087	0.054	0.026	0.037
Mg	3.097	2.465	2.143	2.878	2.519
Ca	1.948	2.038	1.876	1.772	1.727
Na	0.283	0.307	0.226	0.768	0.634
K	0.056	0.243	0.094	0.070	0.027

Note—The oxygen in H_2O_+ and H_2O_- has been excluded from the calculation.

ratios. No relationship between the refractive indices and metamorphic grade has been found. No chemical analysis was made, because actinolite could not be separated from the associated minerals owing to its fibrous habit.

In the transitional area between zones A and B, actinolite coexists with blue-green common hornblende probably in stable equilibrium owing to a miscibility gap between them, as stated before. In the higher-grade part of zone B, the miscibility gap vanishes.

In *zone B*, the observed index γ of blue-green hornblendes ranges from 1.660 to 1.687, and the optic angle over X decreases from about 85° to about 45° with increasing index γ, as shown in Fig. 7. The angle $c\wedge Z$ tends to increase from about 17° to about 23° with increasing index γ. In ordinary thin sections, X=pale yellow, Y=yellow-brownish green and Z=blue-green (bluish green to greenish blue). Hornblendes in the higher-grade part of zone B have generally deeper color than those in the lower-grade part. Two chemical analyses were made as shown in Tables 6a and 6b. SHIDÔ (1958) gives one more analysis from the lowest-grade part of zone B of this district.

In *zone C*, the observed index γ of common hornblendes ranges from 1.664 to 1.684 and the opitic angle ranges from 74° to 88°. The angle $c\wedge Z$ ranges from 15° to 20°. In ordinary thin sections, X=pale yellow, Y=green-yellowish brown, and Z=green, yellow-brownish green or brownish yellow. Two new analyses

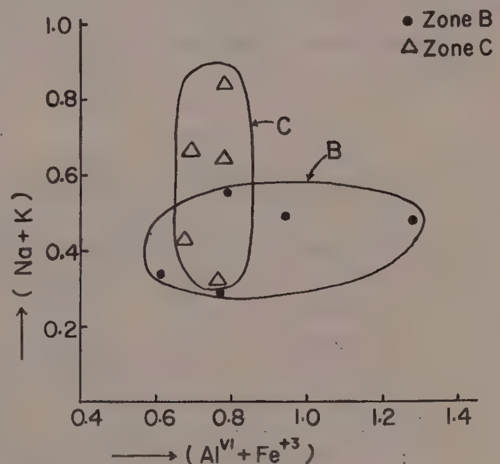

Fig. 9. Composition relation of hornblendes of zones B and C after F. SHIDÔ (1958). The coordinates show atomic ratios on the anhydrous basis of O=23.

Table 7. Pyralspites from pelitic metamorphic rocks of the Gosaisyo-Takanuki district.

Zone	A	B		C					
No.	1	2	3	4	5	(A)	6	7	8
MnO (%)	19.74	16.22	11.86	8.09	6.0	5.93	5.81	5.70	2.87
FeO (%)	13.39	14.01	16.48	19.39	n.d.	26.50	26.64	26.05	29.62
MgO (%)		1.21							3.88
CaO (%)		5.95							2.50
a_0 (A)	11.68	11.66	11.65	11.57	n.d.	11.55	11.58	11.55	11.55
n_D	1.798	1.801	1.799	1.809	1.810	1.815	1.810	1.810	1.809
MnO (%) of associated biotite		0.42		0.32			0.25		0.05

Note—These data are taken mostly from Table 2 of MIYASHIRO's (1953b) paper. The complete analyses of pyralspites Nos. 2 and 8 are given in Table 3 of MIYASHIRO (1953b). (The nos. in the present table are the same as those in that paper.) After the 1953 paper was published, it was found that the calibration of the X-ray powder camera used in the unit cell measurements was very insufficient, and hence the values of a_0 given in that paper involved systematic errors of about 0.3%. The present table shows new accurate values of a_0 in A (not in kX). All the chemical analyses were made by T. MIYASHIRO.

No. 1: Pyralspite from pyralspite-biotite-chlorite-quartz-schist (AM 501028–4a) from Negisi, Tono-mati (zone A). The analysis of the host-rock is shown in Table 5, No. 2.

No. 2: Pyralspite from pyralspite-bearing biotite-quartz-schist with small amounts of sodic plagioclase, muscovite, chlorite, etc. (AM 501020–10b) from Nyuzyo, Tono-mati (middle-grade part of zone B). The analysis of the associated biotite is shown in Table 8. No. 1.

No. 3: Pyralspite from pyralspite-biotite-oligoclase-quartz-schist with small amounts of muscovite, blue-green hornblende, etc. (AM 470623–3) from between Kaiya and Isizumi, Tabito-mura (higher-grade part of zone B).

No. 4: Pyralspite from pyralspite-bearing biotite-K-felspar-quartz-gneiss (AM 491116–1) from between Nyudo and Takinotaira, Hurudono-mura (probably, lower-grade part of zone C).

No. 5: Pyralspite from sillimanite-pyralspite-bearing muscovite-biotite-K-felspar-oligoclase-quartz-gneiss (AM 470802–16) from Yokogawa, Hurudono-mura (zone C). The analysis of the host-rock is shown in Table 5, No. 7.

(A): Pyralspite from pyralspite-porphyroblast-bearing K-felspar-oligoclase-quartz-gneiss with small amounts of muscovite and biotite (AM 510813–4) from Iriyama, Hurudono-mura (zone C).

No. 6: Pyralspite from sillimanite-bearing pyralspite-biotite-oligoclase-quartz-gneiss with small amounts of K-felspar, etc. (AM 491104–2) from Tinokubo (Sinokubo), Hurudono-mura (zone C). The analysis of the associated biotite is shown in Table 8, No. 4.

No. 7: Pyralspite from sillimanite-pyralspite-bearing biotite-muscovite-K-felspar-oligoclase-quartz-gneiss (AM 491105–2) from Daibara, Hurudono-mura (zone C).

No. 8: Pyralspite from pyralspite-bearing biotite-plagioclase (An_{30})-quartz-gneiss (AM 491115–35) from Hottyuka (Hottigaoka), Samegawa-mura (zone C). The analysis of the associated biotite is shown in Table 8, No. 6.

were made as shown in Tables 6a and 6b together with one more analysis from literature. Sphene is common in basic rocks of zone B, whereas it is generally scarce in those of zone C. Probably the Ti of the sphene were mostly absorbed by hornblende in passing from zone B to C, as is suggested by generally higher Ti contents of hornblendes of zone C. The higher Ti content may be a cause of vanishing of bluish tinge in hornblendes of zone C.

The compositional variations of calciferous amphiboles with increasing grade are discussed in detail by Shidô (1958).

All the above statements are concerned with calciferous amphiboles in basic metamorphic rocks. Calciferous amphiboles occur rather rarely in pelitic rocks also. They are similar in color to the calciferous amphiboles of the associated basic rocks.

3. Pyralspite Garnets

Pyralspite garnet (i.e. Ca-poor garnet) occurs in some pelitic and psammitic metamorphic rocks of all the zones. The occurrence is very common in zone C. In a previous paper (Miyashiro, 1953b), a detailed description and discussion of the behaviors of pyralspites in pelitic rocks were already given. Therefore, only a very brief survey will be made below.

As shown in Table 7, nine pyralspites were analyzed from pelitic rocks. The pyralspites from low-grade rocks are highly manganiferous. *With increasing grade of metamorphism, the Mn content decreases and the* Fe^{+2} *content increases rather regularly.* (Probably the Ca content decreases to some extent.) It represents a compositional variation in the direction from spessartine toward almandine. With this compositional variation, the unit cell edge becomes shorter and the refractive index tends to become higher. At least in zone C, pyralspite is stable even in association with K-feldspar.

Metamorphic rocks of ordinary basic compositions do not contain pyralspite. Such rocks have genarally lower Mn/Fe^{+2} and Fe^{+2}/Mg ratios than the pelitic and psammitic rocks, and probably this was the main factor that resulted in the absence of pyralspite in the former and the presence in the latter. Exceptionally, however, some of biotite- and cummingtonite-bearing basic rocks of zones B and C carry pyralspite. These rocks, being comparatively poor in Ca and rich in Al, would have been derived from basic rocks mixed with some pelitic material.

4. Biotite

All the pelitic and psammitic metamorphic rocks contain much biotite. Some basic rocks, especially in zones B and C, also contain biotite.

The index γ of biotites in pelitic and psammitic rocks ranges from 1.635 to 1.660 with maximum frequency between 1.640 and 1.650, whereas that of biotites in basic metamorphic rocks ranges from 1.613 to 1.659 with the maximum frequency between 1.630 and 1.640. No systematic relation was found between the refractive index γ and metamorphic grade.

In zones A and B, biotites have a greenish brown, brown or yellowish brown axial color for Z. In zone C, biotites in pelitic and psammitic rocks have mostly a brown color for Z and rarely a reddish brown or brownish red color for Z, whereas those in basic metamorphic rocks have a brown or yellowish brown color for Z. Thus, *zone C is characterized by the absence of greenish colors and the presence of reddish colors in biotites.*

Table 8a. Biotites from pelitic metamorphic rocks of the Gosaisyo-Takanuki district.

Zone	B			C			
No.	1	2	3	4	5	(T)	6
SiO_2	35.88	35.65	34.97	35.59	34.73	34.13	36.01
Al_2O_3	18.52	17.51	19.04	19.83	17.99	19.74	18.65
TiO_2	0.35	1.78	2.61	1.66	3.21	2.62	2.74
Fe_2O_3	8.85	3.48	1.28	2.52	2.97	2.07	3.46
FeO	13.67	18.15	18.06	18.49	17.93	18.97	16.36
MnO	0.42	0.34	0.47	0.25	0.42	0.33	0.05
MgO	9.06	8.53	9.71	8.16	9.45	7.76	8.31
CaO	0.09	0.69	0.17	tr.	0.13	0.00	0.11
Na_2O	0.82	0.48	0.36	0.21	0.14	0.21	0.97
K_2O	6.24	9.83	10.17	9.72	8.35	9.15	8.57
H_2O+	5.72	3.35	3.31	3.69	4.46	4.30	2.21
H_2O-	0.72	0.14	0.22	0.15	0.22	0.18	1.89
P_2O_5	n.d.	0.10	0.15	0.05	0.17	0.00	n.d.
	100.34	100.03	100.52	100.32	100.17	99.46	99.33
γ_D	1.660	1.641	1.647	1.647	1.658	1.650	1.641

No. 1: Biotite from pyralspite-bearing biotite-quartz-schist with small amounts of sodic plagioclase, muscovite, chlorite, opaque mineral and dust (AM 501020–10b) from Nyuzyo, Tono-mati (middle-grade part of zone B). X=very pale yellow and Y=Z=yellowish brown. This biotite may have suffered slight secondary alteration, judging from its low K_2O and hight H_2O contents. Analyzed by T. MIYASHIRO (MIYASHIRO 1953b)- The analysis of the associated pyralspite is shown in Table 7, No. 2.

No. 2: Biotite from muscovite-biotite-microcline-quartz-schist with small amounts of andesine, apatite, epidote, tourmaline and opaque mineral (AM 470623–12) from Kaiya, Tabito-mura (higher-grade part of zone B). X=pale yellow and Y=Z=dark yellowish brown with greenish tinge. Analyzed by H. HARAMURA.

No. 3: Biotite from tourmaline-muscovite-biotite-quartz-schist with small amounts of apatite and opaque mineral (AM 470623–7) from between Kaiya and Isizumi, Tabito-mura. X=pale yellow and Y=Z=dark brown. Analyzed by H. HARAMURA.

No. 4: Biotite from sillimanite-bearing pyralspite-biotite-oligoclase-quartz-gneiss with small amounts of K-felspar and a radioactive mineral (AM 491104–2) from Tinokubo, Hurudono-mura (zone C). X=pale yellow and Y=Z=yellowish brown. Analyzed by H. HARAMURA. Another determination of MnO gave 0.23 %. The analysis of the associated pyralspite is shown in Table 7, No. 6.

No. 5: Biotite from pyralspite-biotite-oligoclase-quartz-gneiss with a small amount of opaque mineral (AM 470803–8) from Tinokubo, Hurudono-mura (zone C). X= pale yellow and Y=Z=brownish red. Analyzed by H. HARAMURA.

(T): Biotite from biotite-gneiss from Usuki, Hurudono-mura (probably zone C). Z=reddish brown. Analyzed by S. TANAKA (TSUBOI, 1935).

No. 6. Biotite from pyralspite-bearing biotite-plagioclase (An_{30})-quartz-gneiss with small amounts of apatite and opaque mineral (AM 491115–35) from Hottyuka (Hottigaoka), Samegawa-mura (zone C). X=light yellowish brown and Y=Z= deep yellowish brown. Analyzed by T. MIYASHIRO (MIYASHIRO 1953b). The analysis of the associated pyralspite is shown in Table 7, No. 8.

Table 8b. Atomic ratios of biotites of Table 8a calculated on the basis of (O, OH)=24.

Zone	B			C			
No.	1	2	3	4	5	(T)	6
Si	5.24	5.50	5.35	5.40	5.23	5.20	5.65
Al^{IV}	2.76	2.50	2.65	2.60	2.77	2.80	2.35
Al^{VI}	0.43	0.68	0.78	0.95	0.42	0.74	1.09
Ti	0.04	0.21	0.30	0.19	0.36	0.30	0.32
Fe^{+3}	0.97	0.40	0.15	0.29	0.34	0.24	0.41
Fe^{+2}	1.67	2.34	2.31	2.35	2.26	2.40	2.14
Mn	0.05	0.04	0.06	0.03	0.05	0.04	0.01
Mg	1.98	1.96	2.21	1.85	2.12	1.78	1.94
Ca	0.01	0.11	0.03	0.00	0.02	0.00	0.02
Na	0.23	0.14	0.11	0.06	0.04	0.06	0.30
K	1.16	1.93	1.98	1.88	1.60	1.78	1.71
OH	5.51	3.44	3.37	3.73	4.48	4.36	2.31
$Fe^{+3}/(Fe^{+2}+Fe^{+3})$	0.37	0.15	0.06	0.11	0.13	0.09	0.16

Note—Only the H_2O_+ has been regarded as representing (OH).

Six biotites were analysed, all from pelitic metamorphic rocks (Tables 8a and 8b). One more analysis is quoted from literature. Biotites of zone C tend to have higher Ti contents than those of zone B. The brownish red variety in zone C (No. 5) is especially rich in Ti. HALL (1941) emphasized that Ti produces the brown and red colors of biotites. The absence of greenish colors and the presence of reddish colors in biotites of zone C are probably mainly due to their relatively high Ti contents.

Biotites of zone C tend to be poorer in Mn than those of zone B. The following figures are compiled from Tables 7 and 8a:

Biotites of zone B: MnO=0.47, 0.42, and 0.34%.

Biotites of zone C: MnO=0.42, 0.33, 0.32, 0.25, and 0.05%.

This difference in Mn content is due to the change in equilibrium relations between biotite and associated pyralspite with advancing metamorphism (Fig. 10), as will be explained later.

The $Fe^{+3}/(Fe^{+2}+Fe^{+3})$ ratios of the biotites will be discussed later.

SHIDÔ (1958) shows that a biotite from a pelitic schist in the lowest-grade part of zone B in the Nakoso district has 38.42% SiO_2, 1.49% TiO_2 and 0.36% MnO. In such low grades, a decrease in the degree of substitution of Si by Al, as seen in this biotite, may be general.

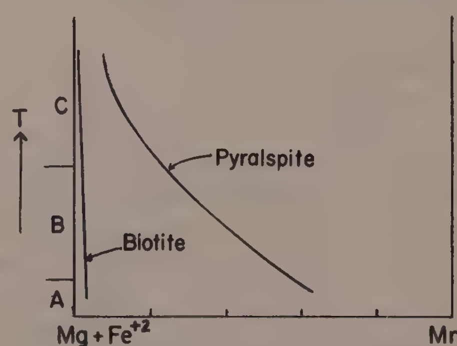

Fig. 10. Schematic equilibrium diagram representing the compositions and amounts of biotites and associated pyralspites. (The Mn contents of biotites are exaggerated.)

5. Muscovite

In pelitic and psammitic rocks of zone A, muscovite (or sericite) is rare, whereas in those of zones B and C, muscovite is more common.

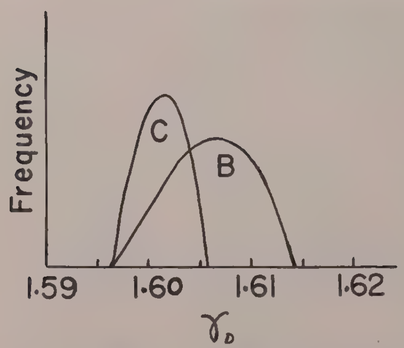

Fig. 11. Frequency curves for the index γ of muscovites in zones B and C of the Gosaisyo-Takanuki and Nakoso districts in the central Abukuma Plateau.

The index γ ranges from 1.597 to 1.614 in zone B, and from 1.597 to 1.605 in zone C. Thus, *the upper limit of the index γ is lower in zone C than in zone B.* This relation is shown in Fig. 11. It is known that the refractive indices of muscovite increases mainly with increasing Fe^{+3} content. Then, we may consider that the maximum Fe^{+3} content of muscovite is smaller in zone C than in zone B.

As stated before, muscovite is stable in the lower-grade part of zone C, whereas it tends to decompose into K-felspar and sillimanite in the higher-grade part of the zone. Therefore, the muscovites of zone C were formed near the high-temperature limit of the stability range of the mineral. It is reasonable to expect that the composition field of muscovite dwindles near the margin of its stbility range, since the vanishing of the composition field of a solid solution mineral with variation in physical conditions means that the mineral becomes unstable. The decrease of the maximum Fe^{+3} content, mentioned above, is probably an expression of such dwindling of the composition field.

6. Andalusite and Sillimanite

Andalusite occurs very rarely in pelitic rocks of zone B and rather rarely in those of the lower-grade part of zone C. Usually it is colorless, An example from the Gosaisyo pass gave $\beta=1.643$ and $2V_X=76°$.

Sillimanite occurs commonly in a small amount in pelitic rocks of almost all parts of zone C. Some pelitic rocks in the lower-grade part of zone C contain both andalusite and sillimanite. Sillimanite is stable even in associatiation with K-felspar. Usually it occurs as minute ascicular crystals with $\gamma=1.676$–1.679.

The transition point from andalusite to sillimanite was within the lower-grade part of zone C, being somewhat lower in grade than the decomposition point of muscovite in this district.

7. Other Minerals

(a) Chlorite

Chlorite is present in almost all rocks in zone A. Its amount and frequency decrease with increasing grade, and in the middle of zone B it practically disappears. The index β ranges from 1.610 to 1.635 and the birefringence $\gamma-\alpha$ ranges from 0.000 to 0.004. Chlorites with β lower than 1.630 show negative elongation in thin sections, whereas those with higher values of β show negative or positive elongation. These optic properties suggest that the chlorites belong to ripidolite and adjacent varieties in WINCHELL's nomenclature. The refractive indices of chlorites in basic rocks increase with the Fe^{+2}/Mg ratios of the host-rock (Fig. 8).

(b) Epidote

Epidote is common in basic metamorphic rocks of zone A and the lower-grade part of zone B. In the higher-grade part of zone B, its occurrence in basic metamorphic rocks is very rare and it may be a product of retrogressive or hydrothermal action. On the other hand, in calcic rocks, epidote occurs com-

monly up to the highest-grade part of zone B, though some of the epidotes embrace grandite, suggesting that they were formed from grandite by retrogressive change.

(c) Cummingtonite

Cummingtonite is rare in basic rocks of zone B, but is very common, though usually not abundant, in those of zone C. Index $\gamma=1.678$–1.680 with Z=very pale yellow. Usually the crystals show polysynthetic twinning and parallel growth with common hornblende.

(d) Anthophyllite

Anthophyllite was found only extremely rarely in metamorphic rocks of basic and ultrabasic compostions in zone C.

(e) K-felspar

K-felspar is nearly absent in zone A, and microcline is rarely present in pelitic and psammitic rocks of zone B, whereas microcline and orthoclase are very common and abundant in pelitic and psammitic rocks of zone C. Their refractive indices are $\alpha=1.518$, $\beta=1.522$ and $\gamma=1.525$ in both zones B and C. For the structural change from microcline to orthoclase, see Shidô (1958).

(f) Cordierite

Cordierite occurs rather rarely in pelitic rocks of zone C. There it is stable even in association with K-felspar. Shidô (1958) reports cordierite in zone B of the Nakaso district, and so the absence of the mineral in zone B of the Gosaisyo-Takanuki district is probably due to the absence of rocks of appropriate compositions.

(g) Tourmaline

Tourmaline occurs rather commonly in pelitic and psammitic rocks of zones A and B, and very rarely in those of zone C. Usually it is pleochroic from green to nearly colorless. (Basic metamorphic rocks contain tourmaline only extremely rarely, but when present it may be in a fairly large amount.)

The greater abundance of tourmaline in lower grades suggests that the boron necessary for its formation was not introduced during the metamorphism but was present in the original rocks. Quartz veins containing axinite and tourmaline run through basic schists at Negisi (zone A)*. Tourmaline-bearing veins were found at several localities within the area of zones A and B. It is not clear whether these veins are genetically related with the tourmaline in pelitic and psammitic rocks.

(h) Clinopyroxene

Clinpyroxenes of the diopside-hedenbergite series occur in calcic rocks of zones B and C.

In limestones, the index α of the clinopyroxene ranges from 1.671 to 1.682, suggesting that the compositions are approximately in the range $Di_{90}Hd_{10}$–$Di_{76}Hd_{24}$. In calcic bands and lenses in basic metamorphic rocks, the index α of the clinopyroxenes ranges from 1.688 to 1.697, suggesting that the compositions are ap-

* These veins, less than 50 cm. wide, are generally concordant to the schistosity of the surrounding rocks, but sometimes show more intense minor folding. They are composed of quartz, albite, axinite, tourmaline and carbonate with minute quantities of chlorite, biotite, epidote and garnet. In the axinite, $\beta=1.680$ and $2V_X=78°$, and in the garnet, $a_0=11.64\,A$ (No. AM 550909-3).

Table 9. Composition of a clinopyroxene.

	Wt. %	Atomic ratios based on O=6		
SiO_2	50.02	1.93		2.00
Al_2O_3	1.98	0.09	0.07	
			0.02	
TiO_2	0.41	0.01		1.02
Fe_2O_3	2.67	0.08		
FeO	9.72	0.31		
MnO	0.83	0.03		
MgO	9.84	0.57		
CaO	23.37	0.96		0.97
Na_2O	0.12	0.01		
K_2O	0.08	0.00		
H_2O+	1.58			
H_2O-	0.04			
	100.66			

Note—This pyroxene was separated from a clinopyroxene-rich lens within amphibolite (AM 470803-12) from Domeki, Hurudono-mura (higher-grade part of zone B). Its optical constants are as follows: $\alpha_D=1.693$, $\gamma_D=1.716$, and $2V_Z=59°$. The analysis shows that $Ca:Mg:Fe^{+2}=52.3:30.7:17.0$. Analyzed by H. HARAMURA. The analysis of the associated hornblende is shown in Tables 6a and 6b, No. 2.

proximately in the range $Di_{65}Hd_{35}$–$Di_{55}Hd_{45}$.

An analysis of a clinopyroxene from a calcic lens is given in Table 9.

(i) Grandite Garnet

Grandite (i.e. Ca-rich garnet) occurs in calcic rocks of zones B and C. In limestones, the index of the grandites ranges from 1.755 to 1.764, suggesting that the compositions are approximately in the range $Gr_{90}And_{10}$–$Gr_{80}And_{20}$. In calcic bands and lenses in basic metamorphic rocks, the index of the grandites ranges from 1.82 to 1.86, suggesting that the compositions are approximately in the range $Gr_{50}And_{50}$—$Gr_{20}And_{80}$. Note that clinopyroxenes and grandites of limestones are much poorer in iron than the corresponding minerals of calcic bands and lenses.

All the grandites and pyralspites of this district are optically isotropic, so far as I observed.

(j) Wollastonite

Wollastonite occurs in limestones of Baba, Hottigaoka (or Hottyuka) and Yunota and in calcic lenses in amphibolite northeast of Daibara, all in zone C. Its formation was probably controlled by the local variation in CO_2 pressure as well as by the temperature prevailing. The index β ranges from 1.629 to 1.634, suggesting that the wollastonites are very poor in iron.

VIII. MINERAL FACIES

1. Preliminary Statement

The mineral assemblages of the metamorphic rocks in the present district will be summarized in this chapter in order to characterize the series of mineral facies to which the rocks belong.

When an assemblage is stable, all the assemblages that are derived by removing a constituent mineral or minerals from it are also stable. Usually some

of the derived assemblages are actually found. From the viewpoint of mineral facies, it is not necessary to enumerate all of the derived assemblages. Then, only some of them will be occasionally referred to.

Mineral assemblage, simplified to some extent, will be shown in ACF and AKF diagrams as proposed by ESKOLA (1915).

2. Mineral Assemblages and Mineral Facies of Zone A

Some basic metamorphic rocks in zone A show the following assemblage:

(1) Actinolite-epidote-chlorite-albite-quartz-biotite-sphene-calcite-opaque mineral. An assemblage derived from this by removing quartz, biotite and calcite is very common, and some other derived assemblages are also common. Calcic bands in basic metamorphic rocks show an assemblage derived from (1) by removing biotite, though calcite is very abundant in this case.

Limestone shows the assemblage calcite-epidote-quartz.

A typical assemblage of pelitic schists is the following:

(2) Pyralspite-biotite-chlorite-muscovite-albite-quartz-graphite-opaque mineral-tourmaline-calcite-fine dust (unidentified).

The assemblages derived from this by removing pyralspite and by removing pyralspite and muscovite are common. Calcite is absent in many cases.

The plagioclases of this zone are albite except in the highest-grade part where oligoclase may occur. The pyralspite garnets are very rich in Mn (MnO=about 20%), being mainly composed of spessartine and almandine molecules.

In the higher-grade part of zone A, blue-green hornblende occurs in association with actinolite.

Figs. 12a and 12b show the ACF and AKF diagrams for rocks in the lower-grade part of zone A, where neither oligoclase nor blue-green hornblende occurs. The rocks in the lower-grade part of zone A belong to the actinolite-greenschist facies. The rocks in the higher-grade part are transitional to a higher facies.

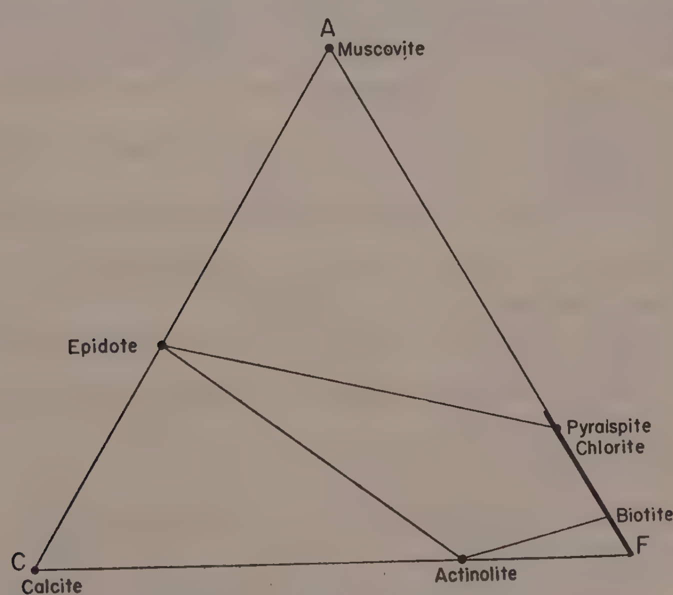

Fig. 12a. ACF diagram for rocks in the lower-grade part of zone A. These rocks belong to the actinolite-greenschist facies.

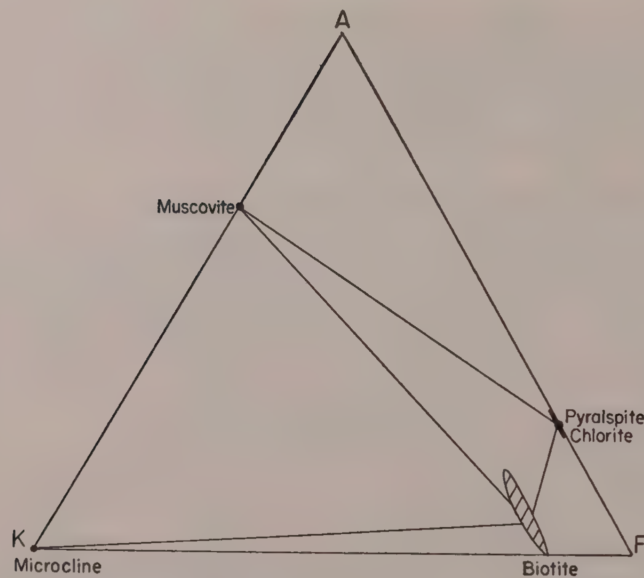

Fig. 12b. AKF diagram for rocks in the lower-grade part of zone A.

3. Mineral Assemblages and Mineral Facies of Zone B

In the lower-grade part of zone B, actinolite coexists with common hornblende and perhaps two phases of of plagioclase (andesine and labradorite) are in stable equilibrium with each other. In the higher-grade part of the same zone, the actinolite disappears and the plagioclases become mixed to form a single phase. Then we will examine below the mineral assemblages in the higher-grade part.

Quartz-bearing biotite-amphibolite shows the following mineral assemblage:

(1) Plagioclase-quartz-hornblende-biotite-sphene-apatite-opaque mineral.

By removing quartz and/or biotite from this, we obtain three common assemblages of amphibolites. Rarely amphibolites contain epidote in addition, but the epidote may have been formed in a retrogressive stage. Cummingtonite-bearing basic rocks show the following assemblage:

(2) Plagioclase-hornblende-cummingtonite-biotite-quartz-opaque mineral with or without pyralspite.

Calcic bands and lenses in basic metamorphic rocks show the following two assemblages:

(3) Grandite-clinopyroxene-epidote-plagioclase-quartz-microcline-calcite-apatite-sphene-opaque mineral.

(4) Clinopyroxene-epidote-plagioclase-quartz-microcline-hornblende-apatite-sphene-opaque mineral.

Epidote is common and abundant in these rocks, but the mineral may be a product of retrogressive reaction.

Some pelitic and psammitic metamorphic rocks show the following two assemblages:

(5) Pyralspite-biotite-muscovite-plagioclase-quartz-tourmaline-apatite-sphene-opaque mineral.

(6) Microcline-biotite-muscovite-plagioclase-quartz-apatite-tourmaline-opaque mineral.

The assemblages that are derived from (5) and (6) by removing muscovite, and

the assemblage that is derived from (5) by removing pyralspite and muscovite are very common in pelitic and psammitic rocks. Andalusite occurs very rarely in association with biotite and muscovite. It seems that microcline does not coexist with pyralspite nor with andalusite in this zone, though the evidence is not conclusive in this respect because of the rarity of microcline.

The plagioclases in the higher-grade part of this zone are usually andesine and labradorite in basic rocks and oligoclase and andesine in pelitic and psammitic rocks. The pyralspites are rich in Mn (MnO=11−17%), being mainly

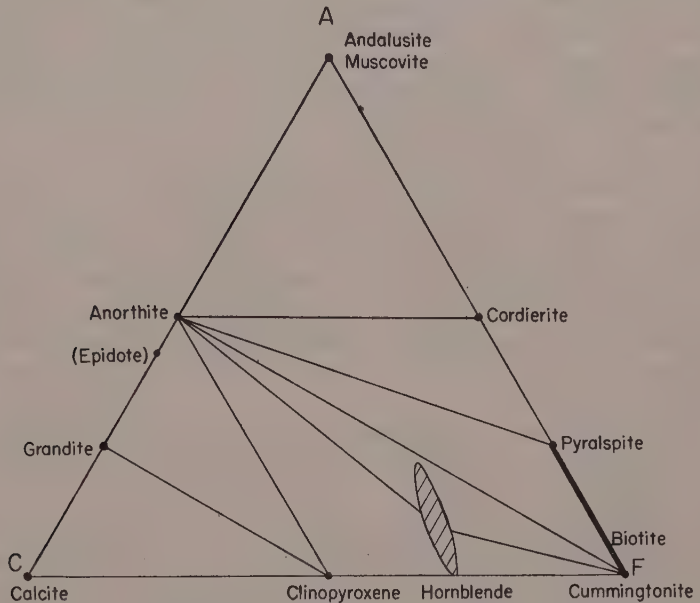

Fig. 13a. ACF diagram for rocks in the higher-grade part of zone B. These rocks belong to a subfacies of the amphibolite facies.

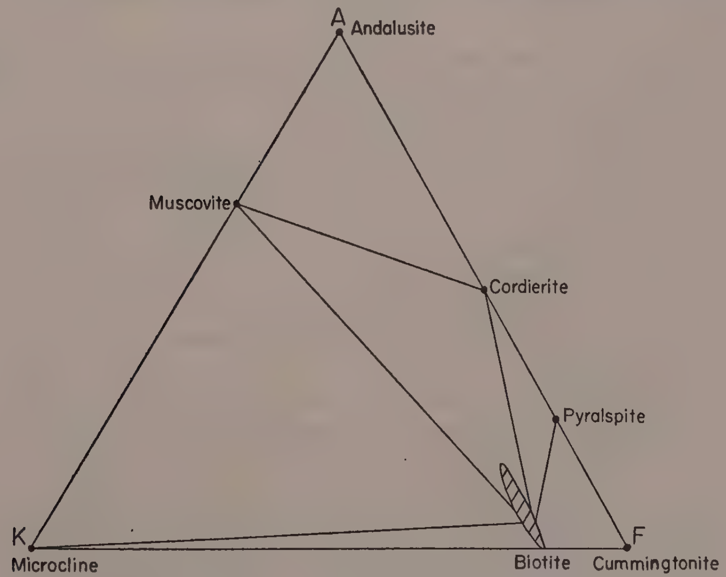

Fig. 13b. AKF diagram for rocks in the higher-grade part of zone B

composed of spessartine and almandine molecules.

Figs. 13a and 13b show the ACF and AKF diagrams for rocks in the higher-grade part of zone B. Andalusite, cordierite, pyralspite and cummingtonite may occur in rocks without K-felspar. On the other hand, andalusite, cordierite, and cummingtonite are perhaps transformed into muscovite and biotite in the presence of microcline. Pyralspite may also react with microcline to produce micas so far as the Mn/(Mg+Fe^{+2}) ratio is not so high.

The rocks in the higher-grade part of zone B belong undoubtedly to the amphibolite facies. Even the rocks in the lower-grade part may be considered to belong to the amphibolite facies, for basic rocks there contain andesine and labradorite. Thus, *in this district, the actinolite-greenschist facies, revealed in zone A, grades directly into the amphibolite facies, revealed in zone B. The epidote-amphibolite is practically lacking.*

4. Mineral Assemblages and Mineral Facies of Zone C

In the lower-grade part of zone C, sillimanite begins to occur, sometimes in association with andalusite, which latter is probably an unstable relic in this case. In the higher-grade part of zone C, andalusite disappears completely and muscovite decomposes. Wollastonite is formed in some calcic rocks of zone C.

Biotite-cummingtonite-amphibolites show the following mineral assemblage:

(1) Biotite-cummingtonite-hornblende-plagioclase-apatite-opaque mineral with or without quartz.

By removing biotite and/or cummingtonite from this, we obtain three common mineral assemblages of amphibolites. The following pyralspite-bearing assemblage was observed only rarely:

(2) Biotite-cummingtonite-plagioclase-quartz-pyralspite-apatite-opaque mineral.

Calcic bands and lenses in amphibolite show the following two assemblages:

(3) Clinpyroxene-hornblende-plagioclase-quartz-apatite-sphene-opaque mineral.

(4) Clinpyroxene-quartz-calcite (or wollastonite).

Some pelitic metamorphic rocks show the following assemblage:

(5) Sillimanite-pyralspite-cordierite-biotite-K-felspar-plagioclase-quartz-apatite-zircon-opaque mineral.

The assemblages that are derived from (5) by removing pyralspite, pyralspite+plagioclase, cordierite, cordierite+sillimanite, or cordierite+pyralspite+sillimanite are common in pelitic and psammitic rocks.

Sillimanite, pyralspite and cordierite are stable in association with K-felspar in the higher-grade part of zone C. On the other hand, cummigtonite perhaps reacts with K-felspar to produce biotite, because biotite is still stable in the higher-grade part of the zone.

Most limestones are composed nearly exclusively of calcite, but impure seams in them shows the following assemblage:

(6) Quartz-calcite-grandite-clinopyroxene-K-felspar-scapolite-apatite-sphene with or without wollastonite.

The assemblage quartz-calcite-wollastonite may have been in equilibrium during metamorphism, because the wollastonite reaction produces CO_2 as the by-product, thus increasing the CO_2 pressure in the environment untill equilibrium would be reached at the temperature prevailing.

The following silica-deficient assemblages were found in some limestones:

(7) Calcite-forsterite-tremolite.

(8) Calcite-forsterite-clinopyroxene-phlogopite.

The plagioclases in the higher-grade part of zone C are usually labradorite and bytownite in basic rocks, and oligoclase and andesine in pelitic and psammitic rocks. The pyralspites are relatively poor in Mn (MnO=about 5%), being mainly composed of almandine molecule. The K-feldspars are microcline and orthoclase.

Figs. 14a and 14b show the ACF and AKF diagrams. These rocks belong to the amphibolite facies.

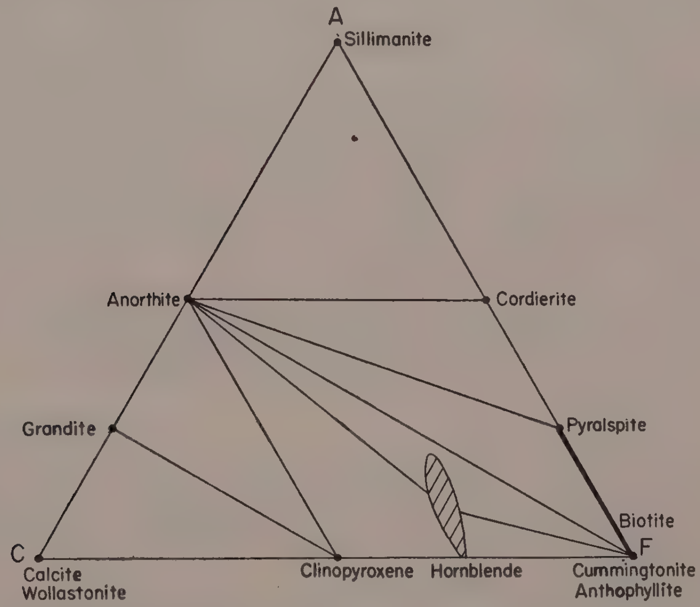

Fig. 14a. ACF diagram for rocks in the higher-grade part of zone C. These rocks belong to a subfacies of the amphibolite facies.

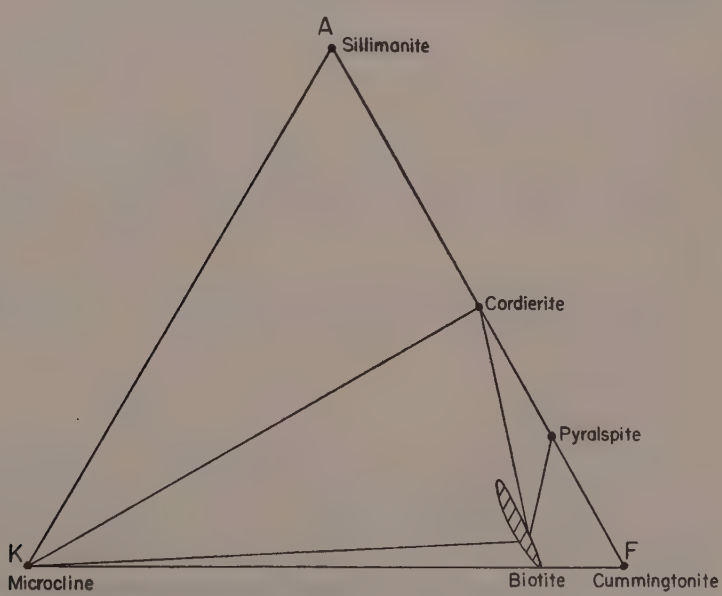

Fig. 14b. AKF diagram for rocks in the higher-grade part of zone C.

IX. MATERIAL MIGRATION DURING METAMORPHISM

1. Evidence for the Narrowness of the Scope of Diffusion

It was described that in zone B, grandite- and/or calcite-bearing assemblages of the calcic bands and lenses are not compatible with the hornblende of the surrounding basic metamorphic rocks. Then, such bands and lenses are usually separated from the surrounding basic rocks on both sides by a clinpyroxene-plagioclase-film, 1–2 mm. thick, free from grandite and calcite. The thickness of the film gives a clear evidence on the magnitude of diffusion during metamorphism. The Mg and Fe^{+2} atoms of the surrounding basic rocks migrated by not more than a few mm. toward the calcic bands and lenses in this case. On the other hand, in zone C, most of the calcic bands and lenses are free from grandite. Probably, at the elevated temperature of zone C, the Mg and Fe^{+2} atoms of the surrounding basic rocks migrated toward and arrived at the center of the calcic bands and lenses, usually not more than a few cm wide, resulting in the conversion of all grandite into clinopyroxene and plagioclase. Even in the highest-grade part of zone C, however, *the scope of migration of Mg and Fe^{+2} atoms was not more than a few cm.*, judging from the distance between the wollastonite-quartz assemblage within some calcic bands and lenses and the surrounding basic rock.

In the Nakoso district, SHIDÔ (1958) shows that corundum and quartz occur in the same thin sections of some aluminous sediments from the lower-grade part of zone C. The minimum distance between the corundum and quartz was 0.28 mm. Then, *the scope of diffusion of Al and Si did not reach 0.28 mm in this case,* because otherwise reaction of the two minerals would have produced andalusite. (Andalusite is present in the thin sections.)

Although the zonal structure of plagioclse in the lower-grade part of zone B may be due to the existence of a miscibility gap in the range of 40–50% An under the conditions prevailing, that in the higher-grades is certainly due to the smallness of diffusion.

All these facts indicate that simple diffusion of materials during metamorphism was very small in scope. The scope of diffusion may have been slightly larger for Mg and Fe^{+2} than for Al and Si.

The bonding energy between a positive ion and an adjacent oxygen ion should become larger as the valency of the positive ion becomes higher and the distance between the centers of the positive and oxygen ions (i.e. total of the ionic radii of the two) becomes smaller. Mg and Fe^{+2} atoms are divalent and have larger ionic radii than Al and Si atoms, which are trivalent and tetravalent respectively. Then, it is reasonable to consider that the diffusion of Al and Si is hindered more severely by the bonding to the oxygen ions abundant in the rocks than the diffusion of Mg and Fe^{+2}.

2. Diffusion of Potassium

I have repeatedly discussed the migration of K during metamorphism. The K contents of metamorphic rocks increase generally with increasing grade, and the increase is probably due to the introduction of K from outside (i.e. from the greater depth or from the associated intrusive masses).

The ions of K are monovalent. K has a larger ionic radius and higher volatility than all the other common rock-forming metals. Then, it is reasonable

that *the diffusion of K is larger in scope and amount than that of all the other common rock-forming metals.*

3. Material Migration due to Bodily Flow

There are numerous quartz veins associated with metamorphic rocks. As the scope of diffusion of Si was very small, the quartz veins must have formed through some process other than diffusion. Probably they were formed by deposition of Si from aqueous solution which was moving by bodily flow. Probably, bodily flow, so far as it exists, is much more powerful in transporting materials than diffusion.

Calcic bands and lenses in basic metamorphic rocks also may have been formed by the bodily flow of aqueous solutions as was discussed before.

In zone C, there are many pegmatitic veins and pockets in metamorphic rocks. Some of the metamorphic rocks are very rich in K-felspar. Probably these pegmatitic and metamorphic rocks were formed by some processes involving the bodily flow of aqueous solution, or possibly of magmatic melts.

X. COMPARISON OF THE METAMORPHISM OF THE GOSAISYO-TAKANUKI DISTRICT WITH THAT OF THE GRAMPIAN HIGHLANDS OF SCOTLAND

1. General Statement

Now I wish to compare the metamorphism of the Gosaisyo-Takanuki district with that of the Dalradian series in the Grampian Highlands of Scotland, with special reference to the physical conditions that prevailed. The metamorphism of the Grampian Highlands has long been studied by many British geologists, especially by Barrow (1893, 1912), Tilley (1925), Phillips (1930), Harker (1932), Wiseman (1934) and Snelling (1957).

The metamorphism of the Grampian Highlands produced kyanite in a lower grade and sillimanite in a higher, whereas that of the Gosaisyo-Takanuki district produced andalusite in a lower grade and sillimanite in a higher. Judging from the stability relations of kyanite, sillimanite and andalusite (Miyashiro, 1949; Thompson, 1955; Clark et. al., 1957), *the latter metamorphism took place under lower solid pressures than the former.*

In the following section, it will be examined how such differences in physical conditions affect the compositions of solid-solution minerals, and it will be shown how the mineral facies series produced differ between the two districts.

2. Calciferous Amphiboles

Wiseman (1934) showed that the calciferous amphibole of basic metamorphic rocks in the chlorite and biotite zones of the Grampian Highlands is actinolite low in Al and alkalies (though he called it hornblende), whereas that of basic rocks in the almandine zone is blue-green common hornblende higher in Al and alkalies. Hornblende in the sillimanite zone is usually green, and brown hornblende occurs in the vicinity of granitic masses. Thus, the Dalradian metamorphism produced the series actinolite—blue-green common hornblende—green common hornblende—brown common hornblende with rise of temperature, just as in the Gosaisyo-Takanuki district. (Recently I confirmed the existence of this series by my own observation of Scottish epidiorites which were kindly sent to me by Dr. S. O. Agrell of the University of Cambridge.)

The formation of aluminous blue-green common hornblende from actinolite and some other minerals generally involves a decrease of total volume in the solid phases. Then, it is to be promoted under higher solid pressures. Thus, the transition from actinolite to blue-green hornblende took place probably at a higher temperature in the Gosaisyo-Takanuki district than in the Grampian Highlands.

3. Plagioclases in Basic Metamorphic Rocks

In the Grampian Highlands, the plagioclase in basic rocks becomes gradually more calcic with increasing grade of metamorphism. WISEMAN (1934) showed that at the entrance to the almandine zone, it has $\gamma=1.540$, corresponding to 5% An. At the highest-grade part of the zone, some of the plagioclases may become andesine. In the kyanite zone, plagioclases are usually andesine and labradorite, sometimes with a more sodic rim. Epidote is common up to the kyanite zone.

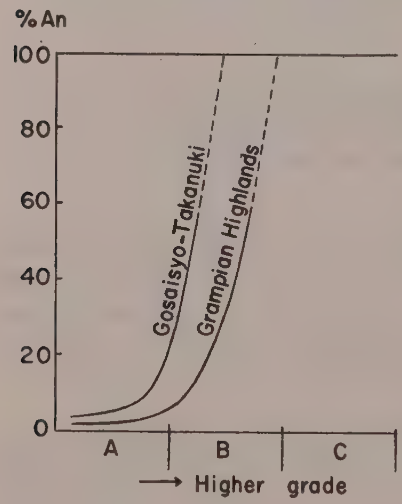

Fig. 15. Variation of the calcic end of the composition range of plagioclase with increasing grade of metamorphism. The grade is measured by the kinds of calciferous amphiboles. A, B and C are characterized by actinolite, blue-green hornblende and hornblende without bluish tinge respectively.

In the Gosaisyo-Takanuki district, the plagioclase is albite in most of zone A, becomes to have 20–30% An at the entrance to zone B, and reaches labradorite in the lower-grade part of zone B. Epidote generally disappears in the middle of zone B.

Fig. 15 shows the comparison of the compositional variation of plagioclase in the two districts. The change of calciferous amphiboles with increasing grade is used as a measure for the metamorphic grade. *The compositional variation of plagioclase with increasing grade is more rapid in the Gosaisyo-Takanuki district than in the Grampian Highlands.*

More calcic plagioclases have a larger volume than the nearly isochemical assemblages of more sodic plagioclases and epidote. Then, the formation of more calcic plagioclases is promoted by lower solid pressures. The compositional variation of plagioclase with rise of temperature should be more rapid in the Gasaisyo-Takanuki district. The curves of Fig. 15 represent the sum of the effects of differenet solid pressures upon calciferous amphiboles and plagioclases.

In the green beds of the Grampian Highlands (PHILLIPS, 1930), zoned plagioclases usually have increasing An content toward the margin, just as in ordinary basic metamorphic rocks of the Gosaisyo-Takanuki district. (In the Grampian Highlands, however, the compositional difference between the core and margin seems to be much smaller.) In the epidiorites of the Grampian Highlands (WISEMAN, 1934), some zoned plagioclases have increasing An ocontents and other zoned plagioclases have decreasing An contents toward the margin. The latter are similar to zoned plagioclases in some basic dykes of the Gosaisyo-Takanuki district, in which the more calcic core probably represents a relic of calcic igneous plagioclase.

4. Pyralspite Garnets

Pyralspite garnets are common and abundant in the almandine and higher-grade zones of the Grampian Highlands, and they are believed to be almandine very low in Mn. In the Gosaisyo-Takanuki district, pyralspites are not so common in low- and middle-grade areas, and the Mn contents of pyralspites in pelitic and psammitic rocks decrease with increasing grade though the contents are much higher up to very high grades than in the Grampian Highlands. This compositional relation is shown in Fig. 16 (1).

As was discussed in another paper (MIYASHIRO, 1953b), the composition field of pyralspite enlarges from the Mn-rich area toward the Fe^{+2}-rich one, and then toward the Mg-rich one, with increasing temperature and solid pressure. The gradual decrease of the Mn content of pyralspite in ordinary pelitic metamorphic rocks with increasing grade is an expression of this relation. It is natural that *the pyralspites in the Gosaisyo-Takanuki district have generally higher Mn and lower Fe^{+2} contents than those of the Grampian Highlands*, since the metamorphism of the former district represents lower presssures than that of the latter.

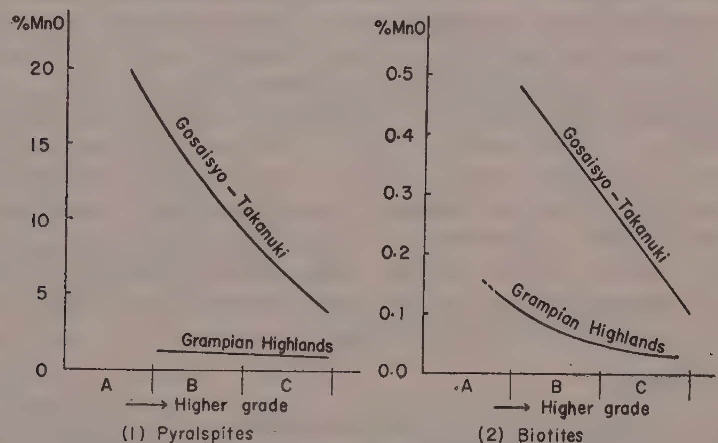

Fig. 16. Idealized diagrams showing the variations in MnO contents of pyralspites and associated biotites with increasing grade of metamorphism. The grade is measured by the kinds of calciferous amphiboles as in Fig. 15.

In the Grampian Highlands, almandine occurs not only in pelitic and psammitic rocks but also in basic metamorphic rocks in the almandine and higher-grade zones, whereas in the Gosaisyo-Takanuki district, pyralspite is almost confined to pelitic and psammitic metamorphic rocks. The basic rocks of the latter district do not contain pyralspite except some cummingtonite-bearing rocks, which occur only very rarely and may represent basic materials mixed with some pelitic ones.

The Mn/Fe^{+2} and Fe^{+2}/Mg ratios tend to be higher in pelitic and psammitic rocks than in basic ones. Probably this is the main factor determining the occurrence of pyralspite in pelitic and psammitic rocks and the absence of it in basic rocks in the Gosaisyo-Takanuki district. Under higher solid pressures, pyralspite would be able to form in rocks with lower Mn/Fe^{+2} and Fe^{+2}/Mg retios, as in basic metamorphic rocks of the Grampian Highlands.

5. Biotites

SNELLING (1957) published the analyses of six biotites in various metamorphic grades in the Grampian Highlands, and suggested that the degree of replacement of Si by Al may decrease in low metamorphic grades. A possibly similar relation in the central Abukuma Plateau has heen mentioned before (p. 253).

Judging from SNELLING's analyses, Mn contents of biotites in pelitic rocks in the Grampian Highlands are generally low (MnO=0.02−0.15%), and tend to decrease with increasing grade. (If the Mn content of a rock is high, the Mn would tend to be used by the production of pyralspite besides biotite. Hence, the Mn contents of biotites have an upper limit practically definite in any particular grade of metamorphism. Probably, the above decrease of the Mn content with increasing grade is an expression of the decrease of the upper limit.)

The Mn contents of biotites in pelitic metamorphic rocks of the Gosaisyo-Takanuki district are much higher than those of the Grampian Highlands, though they tend to decrease with increasing grade of metamorphism, just as in the Grampian Highlands. The highest MnO contents of the six analysed biotites of the Grampian Highlands is 0.15%, whereas seven biotites among the eight analysed ones from the Gosaisyo-Takanuki district have more than 0.15% MnO, the highest value reaching 0.47%. The difference between the two districts is significant. Then, the idealized relation is shown in Fig. 16 (2).

The difference in the equilibrium relation of pyralspites with biotites between the two districts is clearly shown in Fig. 16. Higher solid pressures have similar effects on the equilibrium relation as higher temperatures in this case (see Fig. 10). In other words, the Mn contents of pyralspite and biotite both tend to decrease with increase in temperature as well as in pressure.*

Probably, higher temperature and solid pressure promote the formation of pyralspite, which in turn tends to take more Mn away from biotite, resulting in the decrease of the Mn contents in biotites.

6. Mineral Facies

The metamorphism of the Grampian Highlands gives the well-known series of mineral facies: greenschist facies — epidote-amphibolite facies — amphibolite facies. The greenschist facies is represented by the chlorite and biotite zones, and is characterized by the assemblage albite-epidote-chlorite with or without actinolite in basic rocks. The epidote-amphibolite facies is represented by the almandine zone, and is characterized by the assemblage albite (or oligoclase)-epidote-common hornblende. The amphibolite facies is represented by the kyanite and sillimanite zones, and is characterized by the assemblage andesine (or more calcic plagioclase)-common hornblende.

In the Gosaisyo-Takanuki district, the plagioclase becomes more calcic rapidly in the grade transitional between zones A and B. Thus, andesine or more calcic

* For a similar equilibrium relation between pyralspite and hornblende, see SHIDÔ (1958). She discusses the relation between the compositions of metamorphic calciferous amphiboles and the physical conditions that govern their formation, as summarized below: The (Na+K) content of hornblende increases with increasing solid pressure, though it tends to increase also with increasing temperature, increasing Ab content of the associated plagioclase and increasing degree of undersaturation with silica of the host-rock. Under low solid pressures tschermakite molecule tends to decompose into cummingtonite and plagioclase with rising temperature, whereas under high solid pressures it tends to be transformed to pyralspite.

plagioclase begins to occur as soon as common hornblende becomes predominant among the calciferous amphiboles. Then, the assemblage albite (or oligoclase)-epidote-common hornblende, characteristic of the epidote-amphibolite facies, is practically lacking. Zone A belongs to the actinolite-greenschist facies*, and zones B and C belong to the amphibolite facies.

The amphibolite facies of zone B in the Gosaisyo-Takanuki district closely resembles that of the Orijärvi district in Finland (ESKOLA, 1915). They both contain andalusite and are probably characterized by the incompatibility of andalusite and cordierite with K-felspar (though the evidence is not conclusive in the Gosaisyo-Takanuki district). In zone B, however, quartz and calcite coexist without producing wollastonite, wheras in the Orijärvi district, wollastonite was produced. The amphibolite facies of zone C in the Gosaisyo-Takanuki district differs from that of the Orijärvi district especially in that the former contains sillimanite and is characterized by the coexistence of sillimanite and cordierite with K-felspar, whereas the latter contains andalusite and is characterized by the incompatibility of andalusite and cordierite with K-felspar.

7. Ferric-Ferrous Ratios and Water Pressures

The ferric-ferrous ratios of minerals are an indicator of the conditions, especially water pressure, that prevailed during metamorphic recrystallization.

From the analytical data of biotites in pelitic metamorphic rocks of the Grampian Highlands given by SNELLING (1957), we obtain the following values for the $Fe^{+3}/(Fe^{+2}+Fe^{+3})$ ratios:

Biotite of the biotite zone: 0.15
Biotite of the almandine zone: 0.05
Biotites of the staurolite zone: 0.12, 0.11, 0.03
Biotite of the sillimanite zone: 0.05

On the other hand, the same ratios in the analysed biotites from pelitic metamorphic rocks of the Gosaisyo-Takanuki district are as follows:

Biotites of zone B: 0.37,** 0.15, 0.06
Biotites of zone C: 0.16, 0.13, 0.11, 0.09

Thus, the biotites of the Gosaiyo-Takanuki district tend to have higher $Fe^{+3}/(Fe^{+2}+Fe^{+3})$ ratios than those of the Grampian Highlands.

The Fe^{+2} and Fe^{+3} in biotite were probably in equilibrium with those in the adjacent intergranular film, which in turn were probably in equilibrium with the O_2 in the same film, as shown by the following equation:

$$2Fe_2O_3 \rightleftarrows 4FeO+O_2$$

The O_2 was probably in equilibrium with H_2O and H_2 in the same film because of the following reaction:

$$O_2+2H_2 \leftrightarrows 2H_2O$$

Therefore, higher water pressure during metamorphism should cause higher oxygen pressure, which in turn should result in the higher $Fe^{+3}/(Fe^{+2}+Fe^{+3})$ ratios for biotite, if all the other factors remain constant.

It follows that the metamorphism of the Gosaisyo-Takanuki district may have taken place under higher water pressures than that of the Grampian Highlands.

* The actinolite-greenschist facies is the same facies as the greenschist facies, as the occurrence of actinolite depends largely on the CO_2 and H_2O pressures prevailing.

** SHIDÔ's (1958) biotite from the lowest-grade part of zone B in the Nakoso district has a still higher $Fe^{+3}/(Fe^{+2}+Fe^{+3})$ ratio of 0.56.

The ferric-ferrous ratios of rocks also are related to the water pressure, but the relation is much more complicated because appearance and disappearance of phases are involved in the problem. Probably, the relation could be somewhat simplified by limiting the composition range of the rocks to be treated. Then, attention will be paid below only to ordinary basic metamorphic rocks.

In the Grampian Highlands, the $Fe^{+3}/(Fe^{+2}+Fe^{+3})$ ratios in ordinary basic metamorphic rocks (so-called epidiorites) of the chlorite, biotite and almandine zones range from 0.01 to 0.14 according to the data given by WISEMAN (1934). No systematic variation with metamorphic grade was noticed. On the other hand, in the Gosaisyo-Takanuki district, the same ratios in ordinary basic metamorphic rocks are as follows:

Zone A: 0.29, 0.27, 0.26, 0.22.
Zone B: 0.23, 0.14, 0.13.
Zone C: 0.23, 0.16, 0.02.

Thus, the ratio decreases with increasing grade of metamorphism, and the basic rocks of the Gosaisyo-Takanuki district have generally higher ratios than those of the Grampian Highlands. The ferric-ferrous ratios would tend to decrease with increasing solid pressure as well.

XI. METAMORPHISMS OF THE CENTRAL ABUKUMA TYPE IN THE WORLD

1. General Statement

The present study in the Gosaisyo-Takanuki district and SHIDÔ's (1958) study in the Nakoso district jointly clarify the petrological and mineralogical characters of the regional metamorphism in the central part of the Abukuma Plateau. This metamorphism is regional in areal extent as well as in the distribution of metamorphic zones. The physical conditions that governed it, however, differ from those of the regional metamorphism in the Dalradian series of the Grampian Highlands of Scotland.

The metamorphisms identical and similar in mineralogical characters to that of the central part of the Abukuma Plateau will be called to belong to the *central Abukuma type*. On the other hand, the metamorphisms identical and similar in mineralogical characters to that of the Dalradian series in the Grampian Highlands (except Aberdeenshire and Banffshire as will be mentioned later) will be called to belong to the *Dalradian type*. The central Abukuma type represents lower solid pressures than the Dalradian type.

Metamorphisms of the Dalradian type were described by GOLDSCHMIDT (1915) in the Trondhjem district and by VOGT (1927) in the Sulitelma district, both of Norway. Another example was described by BARTH (1936), BILLINGS (1937) and many others in the northeastern part of the United States of America. The Wissahickon schists of Pennsylvania, described by WEISS (1949), WYCKOFF (1952) and others, also belong to the Dalradian type.

Judging from the existing data, metamorphic rocks of the central Abukuma type are widely developed in Japan and Australia, as will be briefly reviewed in the following sections. Probably the two types of regional metamorphism are nearly equally widespread in the world.

HARKER (1932, pp. 230–235) and WISEMAN (1934) paid attention to the fact that the metamorphism in the northeastern part (Aberdeenshire and Banffshire) of the

Grampian Highlands differs in character from that of the other parts of the Highlands. The former produced andalusite and cordierite in pelitic rock and did not produce pyralspite in basic rocks. Probably, this metamorphism belongs to the central Abukuma type. Then, the two types of regional metamorphism may grade into each other in the Grampian Highlands.

2. Examples in Japan

The regional metamorphism of the Hitati district in the southern Abukuma Plateau is similar in character to that in the central Abukuma Plateau. Some pelitic rocks contain andalusite, sillimanite and/or cordierite. Reliable zonal mapping has not been performed, however.

Sugi (1930) described the pelitic and psammitic rocks of the Tukuba district, about 60 km northeast of Tokyo. The exposed metamorphic terrain is about 12 km wide from east to west. He distinguished three zones in the order of increasing grade as follows:

(1) Zone of spotted biotite slate, mainly composed of quartz, biotite and muscovite.
(2) Zone of schistose "hornfels", which contains quartz, K-felspar, biotite, muscovite, andalusite and cordierite.
(3) Zone of "injection gneiss", which contains quartz, K-felspar, oligoclase (or andesine), biotite, muscovite, sillimanite and cordierite.

The two higher-grade zones are in the amphibolite facies, judging from the fact that they both have calcic hornfelses containing labradorite or bytownite, diopside and common hornblende as intercalated layers between pelitic rocks. (Pyralspite, staurolite and kyanite do not occur.) This metamorphism belongs to the central Abukuma type. The absence of pyralspite would be due to the Mn-poor compositions of the metamorphosed rocks and/or to the too low pressure that prevailed.

The Ryoke terrain is a long metamorphic belt in the Inner Zone of Southwest Japan. The metamorphic rocks of the belt are mainly of pelitic and psammitic types and are similar to those in the Tukuba district, and then zonal mapping could be carried out in a similar way. For example, in the Akaho district of the belt, Murayama and Katada (1957) divided the metamorphic terrain into four zones as follows:

(1) Zone of biotite slate, in which recrystallized minerals include some quartz, biotite, muscovite and chlorite, though recrystallization is very incomplete.
(2) Zone of schistose hornfels I, in which occur quartz, biotite and muscovite rarely with microcline, oligoclase, cordierite, andalusite, and pyralspite. Metamorphic rocks of basic and calcic compositions may contain clinopyroxene and grandite.
(3) Zone of schistose hornfels II, in which occur quartz, oligoclase, microcline, biotite, muscovite and cordierite, rarely with andalusite and sillimanite. Metamorphic rocks of basic and calcic compositions may contain clinopyroxene, grandite and wollastonite.
(4) Zone of banded gneiss, in which occur quartz, oligoclase and sodic andesine, microcline and biotite with smaller amounts of muscovite, cordierite, sillimanite, and pyralspite.

The Mn contents of the analyzed biotites and pyralspites from metamorphic rocks of the Ryoke terrain are comparatively high as shown in Table 10. These biotites are much lower in $Fe^{+3}/(Fe^{+2}+Fe^{+3})$ ratio than those from metamorphic rocks of the central Abukuma Plateau. Then, probably some metamorphisms of the central Abukuma type took place under low water pressures, though others under high water pressures.

Table 10. Biotites in pelitic metamorphic rocks of the Ryoke zone.

No.	1	2	3	4
SiO_2	33.80	35.07	35.06	35.21
Al_2O_3	20.28	21.03	16.53	20.07
TiO_2	3.28	3.36	3.29	2.65
Fe_2O_3	0.75	1.20	0.87	0.68
FeO	21.04	17.22	21.10	16.88
MnO	0.51	0.41	0.48	0.35
MgO	6.84	8.08	8.71	9.78
CaO	0.04	0.04	0.13	tr.
Na_2O	0.13	0.13	0.26	0.37
K_2O	8.56	10.72	9.46	8.94
H_2O+	4.41	2.82	3.10	3.80
H_2O-	0.38	0.35	0.17	0.53
P_2O_5	n.d.	n.d.	tr.	tr.
	100.02	100.43	99.16	99.26
γ_D	1.657	1.649	1.651	1.638

No. 1: Biotite from pyralspite-biotite-oligoclase-quartz-rock with small amounts of apatite, muscovite, sphene and opaque mineral (AM 540812-6A) from Nisi-Takato, Takato-mati, Nagano Prefecture. Analyzed by H. HARAMURA (MIYASHIRO, 1956). The associated pyralspite has 5.98% MnO and 32.47% FeO.

No. 2: Biotite from sillimanite-pyralspite-cordierite-biotite-K felspar-oligoclase-quartz-gneiss with very small amounts of apatite, sphene, opaque mineral and a radio active mineral (AM 540813-1) from Nisi-Takato, Takato-mati, Nagano Prefecture. Analyzed by H. HARAMURA (MIYASHIRO, 1956). The 10.78% K_2O in the original description (MIYASHIRO, 1956) is a misprint for 10.72%. The associated pyralspite has 6.36% MnO and 24.39% FeO.

No. 3: Biotite from biotite-gneiss from Tenryukyo, Nagano Prefecture. Analyzed by S. TANAKA (TSUBOI, 1938).

No. 4: Biotite from schistose cordierite-biotite-albite-K felspar-quartz-hornfels from Karakasa, Tenryukyo, Nagano Prefecture. Analyzed by S. TANAKA (TSUBOI, 1938).

3. Examples in Australia

JOPLIN (1942, 1943) described the pelitic and psammitic metamorphic rocks of the Cooma district in New South Wales. The metamorphism was probably in Ordovician time, and the metamorphic belt trends NS. The metamorphic grade increases toward the granitic masses in the core of the belt. The metamorphic terrain was divided into the following five zones in the order of increasing grade of metamorphism:

(1) Chlorite zone, containing phyllites with chlorite and muscovite.
(2) Biotite zone, containing schists with biotite, muscovite and chlorite.
(3) Andalusite zone, containing schists with andalusite, cordierite, biotite, and muscovite.
(4) Permeation zone, containing gneiss with sillimanite, andalusite, cordierite, orthoclase, biotite and muscovite.
(5) Injection zone, containing injection gneisses with similar minerals as in the preceding zone.

The distance from the biotite isograd to the granitic contact is about 5 miles on

the west side and about 3 miles on the east. There is no doubt that this metamorphism belongs to the central Abukuma type. Pyralspite was not found.

Similar metamorphic rocks were described by VALLANCE (1953a) in the Wantabadgery-Adelong-Tumbarumba district of New South Wales. The metamorphism is probably similar in age as that of Cooma. VALLANCE distinguished four zones in the order of increasing grade as follows:

(1) Low-grade zone, containing slates and phyllites with chlorite and muscovite.
(2) Biotite zone, containing schists with biotite and muscovite.
(3) Knotted schist zone, containing schists with big porphyroblasts of andalusite and cordierite.
(4) High-grade zone, containing gneisses with sillimanite, andalusite, cordierite and K-felspar.

Pyralspite occurs extremely rarely if ever. Small amounts of basic metamorphic rocks were found in various metamorphic grades (VALLANCE, 1953b). They are greenschists in the first two zones, and are amphibolite and hypersthene-labradorite rock (without pyralspite) in the remaining two zones. It is not clear whether the epidote ampibolite facies is absent or not.

XII. ACKNOWLEDGEMENTS

I wish to express my sincere thanks to Prof. Hisashi KUNO for advice and encouragement. I am greatly indebted to Dr. Fumiko SHIDÔ for much information on the petrology of the Nakoso district. Dr. Masao GORAI, Mr. Tatsujiro UNO, and many others gave me valuable advice.

The chemical analyses of rocks and minerals used in this paper were made by Mrs. Tami MIYASHIRO and Mr. H. HARAMURA. Prof. I. IWASAKI and Dr. T. KATSURA made arrangements for analyses by Mr. HARAMURA.

This study was enabled by the Grant in Aid for Scientific Researches from the Ministry of Education of Japan.

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昭和三十三年十一月二十五日 印刷
昭和三十三年十一月三十日 發行

編纂兼發行者 東京大學

東京都新宿区山吹町一八四番地
印刷者 笠井康頼

東京都新宿区山吹町一八四番地
印刷所 國際文献印刷社

東京都中央区日本橋通二丁目六番地
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